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Vol. 13 No. 1 (2025): January 2025

Editorial

Editorial: From Print to Online — A New Chapter for STJ
Editorial Team Journal

Research Articles

Examining the Factors Affecting Building Rehabilitation Projects in India through Confirmatory Factor Analysis
Sushil Kumar Solanki

Economics of Spatial Configuration: A Conceptual Framework for Tenanting Decision of Shopping Malls
Sumanta Deb, Sarbani Sarkar

An Investigation into Visualization of Heritage Sites: A Case of Bai Harir Complex, Ahmedabad
Jaishree Mishra, Vineet Shrivastava, Ramesh Srikonda, Sylvia Romawizuali

Vernacular Settlement as the Smallest Unit in Sustainable Built Environment Research
Dwijomala Hanjabam, Sachin Yadav, Shivani Paliwal, Sylvia Romawizuali

Balancing Expert Vision and Public Desire: Reimagining Public Open Space for Lammual, Aizawl
Emeline Zodingliani Renthlei, Abraham George, Lalmawipuia Khiangte, Lalhruaitluanga Ralte

Climate-Responsive Architecture and Social Cohesion: The Role of the Verandah in Kutch's Traditional Dwellings
Mital Patel, Hemant Wala

Accessibility to Urban Green Spaces for Women Users: A Comprehensive Approach to Urban Planning
Pooja Chaudhary, Manoj Panwar

Street Network Configuration: A Criterion to Assess Walkability Potential of a Traditional and Modern Settlement in Chennai, India
P. Dharmambigai, S. Lakshmi

Urban Neighbourhood Outdoor Environments and Age-friendliness: A Study of Jaipur City, India
Parshant Rehal, Prabhjot Singh Chani, Sonal Atreya, Harsimran Kaur

Does the Physical Environment of an Urban Neighborhood Affect the Social Well-Being of Children? A Pilot Study in Nagpur, India

Vaishali Pedram, Ujwala Chakradeo

Impact of Disasters in Shaping the Vernacular Architecture of Coastal Area
Suchismita Nayak, Parthasarathi Mukhopadhyay, Sanket Ghosh, Soumen Mitra

Determination of Geotechnical Properties of Soil and Disaster Vulnerability Analysis
Lallawmsanga, Lalremruati, Lalhmingsangi, Lalramngheta, K. Zoramthanga, Laldinpuia

Identifying the effect of Success Factors on Predicting Android Mobile App Success on Google Play Store
Anureet Kaur

Optic Nerve Head Info Injected K-Means Method for Segmentation of OD
J. Jency, S. Shunmugan

Enhancing CNC Machining Precision Using AI-Based Process Monitoring and Control
Anand Kumar Singh

Exploring Factors Affecting Land Surface Temperature Using Machine Learning Technique: A Case Study on Meghalayan Terrain
Puja Saha, Teddyson Marbaniang, Amitabha Nath

Handling Gender Bias in Neural Machine Translation: A Focus on English-Khasi Language Pair
Aiusha Vellintihun Hujon, Thoudam Doren Singh, Khwairakpam Amitab

Analysis of Lip Reading of Assamese Digits using Deep Learning
Rabinder Kumar Prasad, Dhiraj Kalita, Zakariya Momin Mondal, M. Tiken Singh, S Md S Askari, Chandan Kalita

Q-Learning-based Energy-Efficient Custom Cooperative Routing Protocol for Underwater Wireless Sensor Network
Payal Karmakar, Rajshekhar Rakshit, Alak Roy, Paresh Kumar Palai

Comparative Analysis of Optimization Models for Transportation Problems
Alok Kumar, Shatrughan Kumar Thakur

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Examining the Factors Affecting Building Rehabilitation Projects in India through Confirmatory Factor Analysis

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Abstract—In India, a high-performance building rehabilitation package must be implemented more quickly in order to achieve the country's sustainable development objective. In order to attain this degree of performance, the construction method for building rehabilitation should move towards industrialized solutions that take into account all construction stakeholders' demands and are unencumbered by current industrial problems. The aim of this study is to investigate and evaluate the fundamental elements and the corresponding challenges that impact building rehabilitation initiatives in India. The purpose of this research is to furnish important insights to the project's stakeholders, empowering them to anticipate and prepare for possible obstacles. While conducting a secondary survey 25 underlying challenges were identified for the execution of building rehabilitation projects in India. The research method involved the study of 38 buildings in the National Capital Region (NCR) to verify and validate these challenges through detailed stakeholder discussion and interviews. The study was analyzed using Confirmatory Factor Analysis (Structure Equation Modelling) using Smart PLS at 0.90 Cronbach's alpha reliability value of the data collected using a questionnaire survey. Further, four significant factors were confirmed at KMO= 0.90. The challenges are grouped under four factors, Project Definition; Project Procurement; Project Risk Management, and Project Closure and Handover. The result shows that factors analyzed and presented significantly exist at the rehabilitation sites.

Keywords: Building Rehabilitation, Service Life, Confirmatory Factor Analysis

INTRODUCTION

Building rehabilitation Project involves the process of repairing, altering, or adding to a deteriorating building to make it compatible for use. As per (GoI-UNDP Disaster, 2007) "Rehabilitation denotes repairing buildings damaged during service or by earthquakes without upgrading the seismic resistance." It is conceivable that rehabilitation could substantially improve and reinforce aspects such as the lifespan of building services, the quality of the living environment, property valuations, and the city's overall image (Hui & Lau, 2011). Financial aspects tend to tip the balance towards building rehabilitation rather than demolition and new construction (Laure & Klunder, 2007), except in those cases where the building is so damaged that rehabilitation costs reach the levels of new construction costs.

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A Project is considered as a successful project when it is completed on time, within budget & to performance specification (Juneja, & Dubey, 2018). Various attempts have been made globally by different researchers to determine critical success factors in construction. There are some variables common to more than one list, but there are certainly no general agreement on the variables (Chan & Tam, 2000). Critical success factors ensure success of a manager or an organization that must be given special and continual attention to bring about high performance (Srimathi *et al.,* 2017). This research aimed to analyse and evaluate the factors affecting the success of Building Rehabilitation Projects in India. Need of the study emerged from the premise that rehabilitation projects require in-depth assessments and meticulous planning to ascertain the extent of rehabilitation needed. Such complexity is rarely encountered in greenfield projects (Ghanaee & Pourezzat, 2013). The frequent occurrence of inadequacies and setbacks in rehabilitation projects necessitates a dedicated effort to identify and understand the root causes of failures (Peng, 2017). The current study delves into rehabilitation projects in India, focusing on understanding the factors influencing their success or failure. Through an in-depth exploration, this study contributes to the comprehension of rehabilitation project dynamics, moving beyond identification to establish the authenticity of factors associated with project failures in the Indian context.

Building rehabilitation Project involves the process of repairing, altering, or adding to a deteriorating building to make it compatible for use. The revitalization of aging urban areas through building rehabilitation is a vital component in fostering sustainability within our cities, offering a cost-effective approach. (Hui *et al.,* 2008) says although buildings do not possess an infinite economic lifespan, the gradual decay of their fabric and structure can be mitigated through the execution of repair and maintenance initiatives.

In the domain of building rehabilitation, a fact emerges as occurrence of the high degree of project failures. A Project is considered as a successful project when it is completed on time, within budget & to performance specification (Juneja & Dubey, 2018). The causes behind an unsuccessful project may vary by the type of project being studied. Distinctive patterns of causes may be associated with the unsuccessfulness of specific types of projects (Pinto & Mantel, 1990). The Project Management Book of Knowledge (PMBOK, 2017), defines the success or failure of a project based on the disparity between what is anticipated from the project both during its execution and after its completion and the actual performance of the project when it is utilized.

Many scholars and construction professionals have been drawn to investigating the factors that can impact the outcome of infrastructure projects over the years. In a study by (Khan *et al.,* 2021) various challenges were identified which are faced in repairs and rehabilitation of dilapidated buildings. The major reasons were Identified as lack of specialization in construction techniques, inefficient resource planning & inefficient project planning & management. Various reasons for delay of rehabilitation projects were identified by (Khatib *et al.,* 2020) as inadequate finance, lack of skilled labour, inefficient project planning & management, inadequate material procurement planning & management, inefficient site management, lack of qualified and experienced personnel, ineffective contract administration, site restrictions & conditions, improper design.

Failure attributes in building projects represent distinct characteristics that indicate deficiencies or inadequacies in the planning, execution, or completion of these endeavours. These attributes are crucial for shedding light on the factors contributing to project failures and facilitating a deeper comprehension of why these initiatives often fall short of their intended success parameters. A significant number of Failure attributes have been identified in this study through extensive literature study Annexure-1.

FACTOR IDENTIFICATION

Thematic analysis was employed to comprehensively examine the failure attributes identified from the existing literature. By discerning commonalities and resemblances among these attributes within the literature, the study ultimately identified four pivotal factors: Project Definition, Project Contract Management, Project Risk Management, and Project Handover, as illustrated in Figure 1 & 2.

Project Definition

The attributes grouped under this factor collectively provide essential information of scope of the overall project. The collective significance of these attributes lies in their role in shaping the project's foundation and ensuring that it is well-defined, feasible, and aligned with its objectives (Doraisamy *et al.,* 2015). Hence, this factor is named as “Project Definition”.

Project Contract Management

Project Contract Type indicates the type or nature of contracts employed in the project. It plays a pivotal role in defining the legal and financial framework of the project (Omran *et al.,* 2012), whether it involves fixed-price contracts, cost-plus contracts, or other contractual arrangements. Procurement procedures are essential in outlining how goods and services are sourced, purchased, and managed within the project (Fantazi *et al.,* 2019). This attribute pertains to how subcontractors are monitored, supervised, and coordinated to ensure they meet project requirements and timelines (Omran *et al.,* 2012).

They offer insights into the strategies, procedures, and practices employed to effectively manage contracts, which is vital for ensuring that contractual agreements are upheld and that the project progresses smoothly within the established contractual framework (Doraisamy *et al.,* 2015). Hence, this factor is named as "Project Contract Management".

Project Risk Management

Risk Identification pertains to the process of identifying potential risks or uncertainties that may impact the project. Quality Assurance (QA) and Quality Control (QC) processes are vital for ensuring that specialized work within the project meets defined quality standards (Hui *et al.,* 2008). Effective risk management involves systematic procedures for assessing, mitigating, and monitoring risks throughout the project's lifecycle (Shah *et al.,* 2021). This attribute delves into the strategies and methodologies employed to manage and minimize project risks. Change management processes are essential for handling alterations or modifications within the project (Naaranoja & Uden, 2007). Effective management practices are crucial for overseeing project activities and ensuring smooth operations. Communication plays a vital role in risk mitigation (Fantazi *et al.,* 2019).

The cluster of attributes falling under the third factor is closely associated with the management of risks within the project. These attributes collectively offer insights into various aspects of risk identification, mitigation, and management practices that are essential for effective project execution (Juneja, & Dubey, 2018). Hence, the third factor was named as "Project Risk Management".

Project Handover

The attributes grouped under this category offers insights into the critical phase of transitioning from construction or implementation to the operational use of the project highlighting the importance of assessing project success, evaluating its performance post-occupancy, and conducting functional testing to ensure its intended functionality (Peng, 2017).

DATA COLLECTION

Questionnaire Survey

The initial pilot study conducted subsequent to a thorough literature review, involved structured interviews with industry participants. The professionals who participated in the pilot survey had more than 15 years of working experience in construction projects. Following the pilot study, refinements were made to the questionnaire based on the feedback received. To select the case study samples, the researchers approached various stakeholders, including clients, professional, and contractors operating in the New Delhi region. Table-2 provides information about 30 different case studies of different rehabilitation sites in the New Delhi region approached for this study.

The questionnaire was in a Close Ended Format. This questionnaire which had 25 key attributes was crafted based on the inputs from the pilot study. To measure the impact of these attributes, a 5-point Likert scale was employed, a widely recognized tool for assessing individuals' attitudes, opinions, or perceptions.

SAMPLE SIZE

The survey was circulated amongst the various stakeholders of the identified sites. A total of 198 samples were collected. This sample size satisfies the minimum ratio of items to respondents (ratio of 1 : 5) for carrying out factor analysis (Hair, 2009). Sample size can also be calculated by Cochran's equation. It was found out that the sample size should be 203, which was rounded up to 200. So, the sample size taken was adequate as per Cochran's equation.

Data Analysis through Smart PLS SEM

CFA was performed using SEM as implemented in PLS to test the theoretical model's reliability and validity as shown in Figure 1. PLS path model (drawn in Smart PLS software) after PLS Algorithm calculation with independent variables (failure attributes), dependent variable (latent factors), the relationship among variables and all indicators of variables are shown in Figure 2.

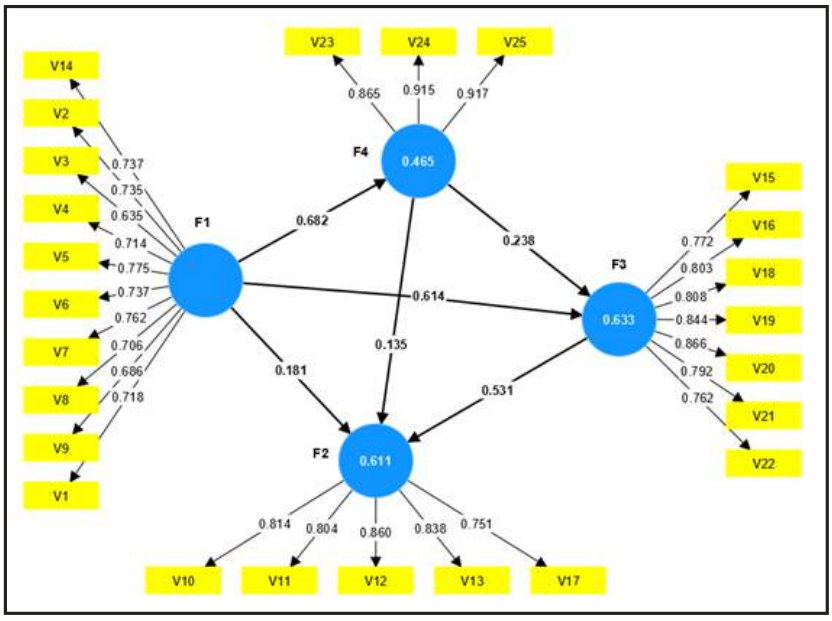

Fig.1: Study Model (*Source:* Author)

Individual Item Reliability and Convergent Validity

The convergent validity of each latent construct was assessed in the context of Partial Least Squares Structural Equation Modeling (PLS-SEM) by comparing the values of the average variance extracted (AVE), composite reliability (CR) scores, and Cronbach's alpha coefficient to predetermined thresholds of 0.70, 0.70, and 0.50, respectively (Hair *et al.,* 2011) and (Wong, 2013) Cronbach's alpha & Composite reliability should be higher than 0.70 and AVE should be higher than 0.50. Table 1 demonstrates that all reflective constructs exceeded these threshold values.

As per (Hair *et al.,* 2011) and (Wong, 2013) Outer loadings should be higher than 0.70. In Table 2, it is evident that the outer loadings for all items exceeded the 0.7 threshold, except for V3 and V9. However, as per (Mehta, 2022) these specific items were retained due to considerations related to content validity. In summary, the measurement scales demonstrate strong convergent validity and internal consistency overall.

MEASUREMENT MODEL

The evaluation of a measurement model relies on the premise that if there is uncertainty about whether the measures accurately reflect the intended constructs, it is not advisable to employ them to analyze the structural relationships (Hair *et al.*, 2011) (Wong, 2013).

Table1: Individual Item Reliability and Convergent Validity Values (*Source:* Author, 2023)

	Cronbach's alpha	Composite reliability (rho_a)	Composite reliability (rho_c)	Average variance extracted (AVE)
Project Definition **(F1)**	0.897	0.901	0.915	0.52
Project Contract Management **(F2)**	0.872	0.873	0.908	0.663
Project Risk Management **(F3)**	0.911	0.912	0.929	0.652
Project Handover **(F4)**	0.881	0.881	0.927	0.809

Table 2: Outer Loading Values (*Source*: Author, 2023)

Failure Attributes	Project Contract Management	Project Definition	Project Handover	Project Risk Management
V10		0.814		
V11		0.804		
V12		0.86		
V13		0.838		
V14	0.737			
V15			0.772	
V16			0.803	
V17		0.751		
V18			0.808	
V19			0.844	
V2	0.735			
V20			0.866	
V21			0.792	
V22			0.762	
V23				0.865
V24				0.915
V25				0.917
V3	0.635			
V4	0.714			
V5	0.775			
V6	0.737			
V7	0.762			
V8	0.706			
V9	0.686			
V1	0.718			

DISCRIMINANT VALIDITY

The analysis findings are displayed in Tables 3 and 4. (Fornell & Larcker, 1981) if the square root of the AVE in each latent variable has a higher correlation value than other values among the latent variables, this can be utilized to show discriminant validity. Table 4 reveals that the Fornell Larcker criteria of the diagonal elements to be the highest value is fulfilled. Similarly, in HeterotraitMonotrait Ratio (HTMT) is a measure of similarity between the latent variable. As per (Hair *et al.,* 2011) and (Wong, 2013) HTMT values should be less than 0.85. In Table 5, it is evident the HTMT values are less than the threshold limit of 0.85. Consequently, these observations indicate that there are no issues concerning discriminant validity.

Structural Model

The structural model represents the relationship between latent variables hypothesized in the research model (Rahman *et al.,* 2015). The R2 values and the degree of significance of the path coefficients, which explained the variance of endogenous latent variables, were the primary evaluation criteria for the structural model. (Hair *et al.,* 2011).

Collinearity Statistics

To determine redundancy, researchers should examine the degree of multicollinearity in the formative indicators (Cassel *et al.,* 1999; Grewal *et al.,* 2004). As a rule of thumb, researchers need to have a VIF of 5 or lower (i.e., Tolerance

level of 0.2 or higher) to avoid the collinearity problem (Hair *et al.,* 2011). Table 5 shows that all VIF scores were less than the threshold of 5.

Path Coefficients, R-Square & f-Square

PLS-SEM does not presume that the data are normally distributed. In order to get standard errors for hypothesis testing, PLS uses nonparametric bootstrapping, which is repeated random sampling with replacement from the original sample to construct a bootstrap sample. It is possible to assess the significance of the computed coefficients in PLS-SEM thanks to the bootstrap sample (Henseler, 2017). According to Hair *et al.* (2011), there should be 5000 bootstrap "samples" and the same number of bootstrap "cases" as there are valid observations. Using 5000 samples, this study ran a bootstrap analysis in Smart PLS. The analysis result in Table 6 shows the P-values which are less than 0.05 which indicates that the next step can be followed.

The coefficients of the PLS structural version may be interpreted as standardized beta coefficients of least squares regressions. Paths that are nonsignificant or display symptoms and symptoms opposite to the hypothesized course no longer guide a previous hypothesis, while extensive paths displaying the hypothesized course empirically guide the proposed causal relationship (Hair *et al.*, 2011). Table 7 indicates that zero isn't always protected withinside the bias corrected that means that the course coefficient is extensive.

According to (Hair *et al.*, 2011), an R^2 value between 0.02 - 0.12 is weak, 0.13 - 0.25 is moderate, and 0.26 & above is substantial. Table 8 specifies the values of R^2, which are substantial explaining the variance in the endogenous variable explained by the exogenous variables. The Cohen's Indicator (f^2) is obtained by the inclusion and exclusion of model constructs (one by one). Values of 0.02, 0.15 and 0.35 are considered small, medium, and large respectively (Hair *et al.*, 2011). Table 9 shows the f^2 values.

Table 3: Fornell Larcker Criterion (*Source:* Author, 2023)

	Project Definition (F1)	Project Contract Management (F2)	Project Risk Management (F3)	Project Handover (F4)
Project Definition (F1)	0.776			
Project Contract Management (F2)	0.686	0.814		
Project Risk Management (F3)	0.721	0.761	0.808	
Project Handover (F4)	0.682	0.607	0.656	0.899

Table 4: Heterotrait Monotrait Ratio (HTMT) (*Source:* Author, 2023)

	Project Definition (F1)	Project Contract Management (F2)	Project Risk Management (F3)	Project Handover (F4)
Project Definition (F1)				
Project Contract Management (F2)	0.767			
Project Risk Management (F3)	0.849	0.848		
Project Handover (F4)	0.765	0.687	0.732	

Table 5: Variance Inflation Factor (VIF) values of Outer Model (Source: Author, 2023)

V10	V11	V12	V13	V14	V15	V16	V17	V18	V19
2.144	2.122	2.608	2.368	1.842	1.944	2.195	1.556	2.184	2.795
V2	V20	V21	V22	V23	V24	V25	V3	V4	V5
2.444	3.15	2.219	1.97	2.02	2.989	2.944	1.76	1.878	2.14
V6	V7	V8	V9	V1					
1.916	2.021	1.841	1.706	2.244					

Table 6: Path Coefficients-Mean, Std Dev, T-value, P-value (*Source:* Author, 2023)

	Original sample (O)	Sample mean (M)	Standard deviation (STDEV)	T statistics (|O/STDEV|)	P values
F1 -> F2	0.181	0.188	0.081	2.236	0.025
F1 -> F3	0.614	0.619	0.058	10.518	0
F1 -> F4	0.682	0.683	0.042	16.072	0
F3 -> F2	0.531	0.527	0.085	6.265	0
F4 -> F2	0.135	0.133	0.078	1.731	0.044
F4 -> F3	0.238	0.234	0.062	3.815	0

Table 7: Path Coefficients-Confidence Interval bias corrected (*Source:* Author, 2023)

	Original sample (O)	Sample mean (M)	Bias	2.50%	97.50%
F1 -> F2	0.181	0.188	0.006	0.026	0.34
F1 -> F3	0.614	0.619	0.004	0.494	0.724
F1 -> F4	0.682	0.683	0.001	0.583	0.753
F3 -> F2	0.531	0.527	-0.004	0.354	0.69
F4 -> F2	0.135	0.133	-0.002	-0.019	0.285
F4 -> F3	0.238	0.234	-0.004	0.116	0.363

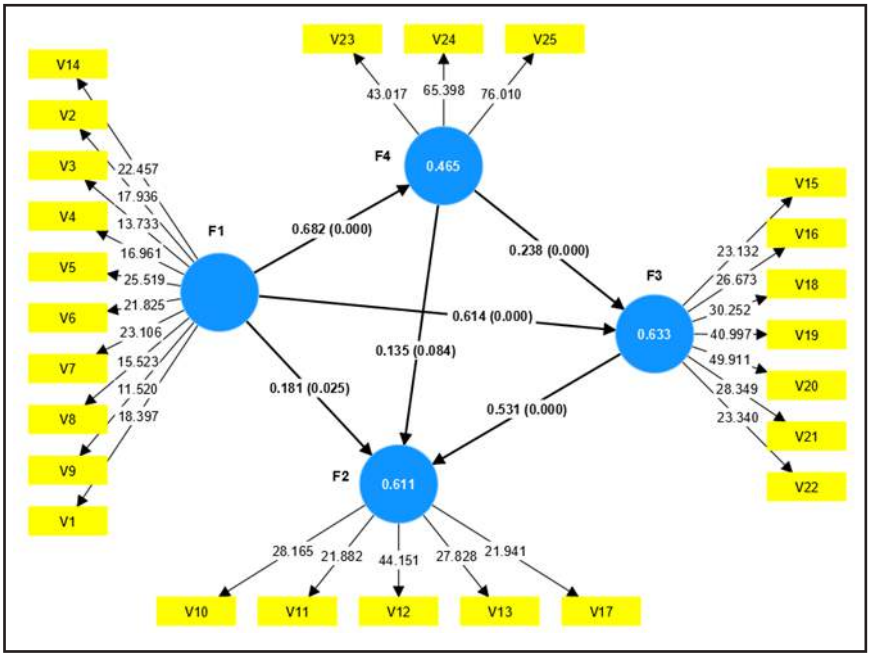

Fig. 2: Study Model After Bootstrapping (*Source:* Author, 2023)

Table 8: R-Square overview (*Source:* Author, 2023)

	R-square	R-square adjusted
F2	0.611	0.604
F3	0.633	0.629
F4	0.465	0.462

Table 9: f-Square (*Source:* Author, 2023)

	F1	F2	F3	F4
F1		0.029	0.55	0.868
F2				
F3		0.266		
F4		0.023	0.082	

Table 10: f-Square (*Source:* Author, 2023)

	Saturated model	Estimated model
SRMR	0.063	0.063
d_ULS	1.301	1.301
d_G	0.63	0.63
Chi-square	618.434	618.434
NFI	0.809	0.809

Model Fit Indices

The The analysis findings are displayed in Tables 10. The value of the SRMR was below the recommended threshold value of 0.080 (Benitez *et al.,* 2020) which indicates it has less residual error. The NFI value is nearer to 0.9. All these indices indicate that the model is fit and good.

DISCUSSION

The research has substantiated the conjecture that success in rehabilitation projects hinges on the strategic consideration of four pivotal factors: Project Definition, Project Contract Management, Project Risk Management, and Project Handover. Undoubtedly, these elements play a crucial role in shaping the outcome of rehabilitation initiatives. Nevertheless, it is imperative to recognize and address the inherent limitations of the study. Notably, the data collection process for the survey was confined to the geographical confines of the National Capital Region (NCR) in India. While this localized approach offers valuable insights, it falls short of providing a comprehensive understanding applicable across the entire country. To enhance the robustness and applicability of the findings on a broader scale, it is imperative to engage in a more expansive and inclusive data collection effort, spanning diverse regions of the country. Such a comprehensive approach ensures not only cross-cultural validation but also facilitates the generalization of the study's conclusions to a more representative and diverse spectrum of the population, thereby encouraging the overall credibility and relevance of the research outcomes.

CONCLUSION

In the context of Building Rehabilitation projects , the achievement of success is a multifaceted and intricate undertaking, characterized by numerous factors and considerations. A clear project definition lays the groundwork for a well-defined scope, and effective contract management ensures the adherence to agreements. Proactive risk management helps mitigate uncertainties, and thorough handover and post-occupancy evaluations guarantee the fulfilment of project objectives. This research has expanded the understanding of these factors and their profound impact on the success of building rehabilitation projects in Indian context. Construction project managers

and stakeholders should be exceptionally attentive to these factors and attributes. Recognizing their significance and integrating them into project planning and execution processes is imperative for attaining successful outcomes within the intricate and evolving landscape of building rehabilitation projects. A comprehensive approach to addressing these factors empowers stakeholders to navigate challenges, mitigate risks, and enhance the prospects of successfully completing projects with enduring functionality.

FUTURE SCOPE

A comprehensive exploration is undertaken to elucidate the potential avenues for future research endeavours within the purview of this particular subject matter. The attributes/challenges linked with the identified factors were identified in the current research. Future scope of this study will be to further study in depth the challenges identified by the researcher and propose mitigation strategies for the same. The research approach adopted for the mitigation strategies can be a theoretical approach as the research will involve refining a particular theory and improve an action.

CONFLICTS OF INTEREST

No conflict of interest was declared by the authors.

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Economics of Spatial Configuration: A Conceptual Framework for Tenanting Decision of Shopping Malls

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Abstract—A shopping mall is an agglomeration of discrete tenant stores with varied capacities of rental payment. The complexity of mall management lies in fulfilling the profit maximizing objective of the individual tenant stores and the mall as a whole. This two-step objective of profit maximization is attained through tenant-mix decision. Tenant stores of suitable size and rental payment should be placed in a shopping mall to generate maximum profit for that store and to earn maximum revenue for the shopping mall at the same time. The location and area allocation decisions are essentially spatial but no parameters of spatial configuration are used in predicting the tenanting decision. The mall management handles this decision in a subjective and generalized way. Only spatial variable acknowledged in retail literature is metric distance which predicts the most significant variable for tenanting decision, foot fall. Syntactical analysis of spatial configuration in the field of built environment on the other hand attempted to predict movement and foot fall within a built space. The results of studies in these two disciplines are end in themselves. The findings from one discipline do not help decision making in another. This research attempts to bridge the gap between retail management and syntactical analysis of space and attempts to include spatial parameters in taking strategic decisions.

Keywords: Agent based simulation (ABS), Metric mean shortest path angle (MMSPA), Tenant-mix, Through vision (TV), Visibility Graph Analysis (VGA).

INTRODUCTION

A shopping mall is an agglomeration of different stores, with varied rental payment potential, managed by an individual operator. Maximization of profit is the objective of the individual tenant stores as well as for the entire shopping mall. Tenant mix is the methodology adopted by mall management professionals to meet the dual objective. Research results in the field of retail management (Garg & Steyn, 2014 and Yiu & Xu, 2012) ventured to develop an "ultimate tenant mix" as a potential tool. The earlier researches on tenant-mix resorted to inter-store externality in explaining the agglomeration of stores (Benjamin , 1992; Eppli & Shilling, 1995 and Pashigan & Gould, 1998) without focussing on spatial configuration. These findings are case specific and non-generalizable. The leasing decisions within an organized shopping mall consist of selection of right mix of stores, space allocation, rent determination and location (Dawson, 1983). These should be finalized at an initial phase of development (Guy, 1994 and Beyard & O'Mara, 1999). This paper explores the economic potential of spatial configuration in a shopping mall and proposes a conceptual framework for designing tenant-mix relying on the configuration of the built space.

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In reality, the design of a shopping mall involves complexities and requires input from a diverse group of professionals. The designer works on the concept and accommodates the requirements within an aesthetically appealing spatial envelope. The built space is converted into an efficient shopping mall with the help of retail and mall management professionals. Locating stores and allocating areas are spatial parameters (e.g. Roulac, 1996). Nevertheless, spaial configuration is not fully explotd in taking tenanting decisions; they are taken on a rule-of-thumb. Retail resaerchers (Carter & Haloupek, 2002; Carter & Vandell, 2005 and Ingene & Ghosh, 1990) acknowledged metric distance as the only spatial vaiable in determining tenant mix as it exhibits high correlationship with foot-fall. Space syntax analysis, on the other hand provides the spatial logic behind movement (which results in footfalls or gate counts at different places) through quantifying configuration and relating that with gate counts. The gap between the two approaches (retail management and architecture) needs to be bridged for a logical tenanting decision making framework. Gate counts can be used for predicting profit function of a store and the syntactic values of configuration can be used to analyse and predict footfalls or gate counts. It is possible to develop a tenanting decision making framework relying on those findings, where the layout of the mall and data regarding stores for occupation are available, under conditions of maximising profit of the tenant stores and maximising revenue earning for the developer.

LITERATURE REVIEW

Significance of Tenant Mix

McCollum, 1988 defined tenant-mix as a collection of different stores with varying capacities of rental payment within a shopping mall such that they help in achieving financial viability of the mall besides maximizing their own profits. Maximization of revenue from a shopping mall therefore relies on the efficiency of the tenant-mix decisions (Brown, 1992; Garg & Steyn, 2014). Research findings also suggest that tenant-mix impact selection of malls (Bellenger, *et al.,* 1977), stimulate repeat purchase behaviour (Stoltman*, et al.,* 1991) create imageability (Finn & Louviere, 1996) and finally affect customer gratification (e.g. Abghari & Hanzaee, 2011). The benefit of agglomeration is measured through store externalities by Wheaton (1999). This externality is the positive or negative impact on each other due to proximity.

Configurational studies on shopping malls and the significance of movement

Brown, 1991 and Sim & Way, 1989 focused on movement of customers or foot-fall as another important factor in influencing tenanting decisions. They adopted bid-rent in explaining tenanting decision relying on customer footfall. Carter & Vandell (2005) and Eckert & West (2008) explained internal configuration of shopping malls in terms of footfall. These studies relied on the inverse relationship between footfall and metric distance. Carter & Vandell (2005) adopted metric distance measure from Carter and Haloupek (2000) as a deciding factor and assumed in their model the maximum foot fall near the center of the mall with gradual decline to a minimum at the two ends. The studies, which considered the potential of footfall in projecting tenanting decisions, considered the theories of urban structure, i.e., central place theory (Christaller, 1966), bid-rent theory by Alonso (1964) in a 'closed city' form. Nevertheless, the methodology is applicable for a linear mall with entry point in Centre and is not sufficient for accommodating complexities in modern mall configurations.

Movement and the significance of Visibility measures and Agent Based Simulation

Retail literature, which relied on urban spatial structure, espouses the supremacy of footfall in tenanting decision making (e.g. Brown, 1999; Carter & Vandell, 2005) necessitating prediction of movement. Measuring navigation has always been critical in architectural and planning studies and is done through several methods. Unlike other methods, space syntax method is based on quantification of spatial configuration for understanding social encounters and co-presence. Research results for indoor movement (Haq & Zimring, 2003; Hölscher, *et al.,* 2012) established the efficacy of syntactic measures in predicting movement. Research findings of Hillier (1996) and Turner, *et al.* (2001) corroborated that syntactic values are better predictors of movement compared to the metric measures.

Among other syntactic measures visibility measures exhibit better results in predicting indoor movement (Ittelson, 1973, Appleton, 1975; Desyllas & Duxbury, 2001; Turner & Penn, 1999, Parvin, *et al.* 2007) and verified for artificial organisms (Yeap & Jefferies, 1999) and established a strong relationship between visibility and accessibility. The Visibility Graph Analysis (VGA) is a widely used tool (Batty,

et al., 1998; Turner & Penn, 1999; Turner, 2001; Turner, *et al.,* 2001; Desyllas & Duxbury, 2001) in studying movement relying on inter-visibility and is a good predictor of movement and accessibility (Turner & Penn, 1999; Desyllas & Duxbury, 2001; Parvin, *et al.* 2007). VGA is conducted on a plan diagram by overlaying a grid of points. The analysis yields several visual and metric measures of center points of those grids. Two measures of VGA have been identified for explaining navigation and prediction of gate counts: through vision (TV) and metric mean shortest path angle (MMSPA). TV is the line of inter-visibility between two vantage points (Turner *et al.,* 2001) and corresponds well with human movement (Peponis, et al., 1990; Haq, 2003; Conroy Dalton, 2003; Saito, *et al.,* 2017). MMSPA measure is selected for 'realistic' notion to movement (Turner, 2001) over metric distance, which is the traditional spatial variable in retail research (Carter & Vandell, 2005).

Turner & Penn (2002) recommended agent based simulation with visibility information. Agents or automata were used in these researches as proxy for pedestrians with the accessibility of visual information from VGA which is equivalent to vision. Therefore, by providing vision, the agents simulate a human movement around a built environment (Conroy, 2001). The agent based simulation results correlates well with actual human movement (Turner & Penn, 2002 and Turner, 2003).

METHOD

The basic research objective is to exploit the potential of configuration of built environment of a shopping mall to influence tenant-mix decisions. Therefore, the total revenue earning from a shopping mall has to be stated in terms of parameters of built environment. This is approached by a two-step methodology. Traditional bid-rent function is used to establish the total revenue function and the visual configurational analysis is adopted to establish the relationship between gate counts or foot-fall at a particular location in terms of spatial configurational parameters.

Bid Rent Analysis

The bid-rent analysis in its classical form establishes the relationship between profitability of a store based on its location. The objective of a store in a shopping mall just like "firms in (the) city" (Carter & Vandell, 2005) is to maximize profit. The profit function of a store in a mall is stated as (Deb, 2019):

$$\pi = V - C - R \quad (1)$$

Where π = profit, V = Revenue, C = Cost and R= total rent

$$So,\ V = p.q$$

Where, p = Average unit price of commodities and q = total sales quantity for an accounting period

The total sales quantity (q) again depends on the number of buyers and the amount of average purchase:

$$q = N_b.a$$

Where N_b = number of buyers
a = Average sales quantity per buyer

N_b, again, depends on the gate counts or footfalls and conversion rate of the store, i.e., number of buyers/ total gate counts:

$$N_b = g^k.c$$

g = gate counts or foot fall
c = conversion

k is a constant that ranges between $0 < k < \infty$. It is essentially inter store externality. For convenience of calculation, we will further assume that there is no inter-store externality or, $k = 1$.

Total sales quantity, q can be expressed as:

$$q = a.g.c$$

Conversion rate increases with increase of store area but at a decreasing rate. Carter & Vandell, 2005 showed the decreasing pattern from a dataset of Urban Land Institute, 1993 and that can be expressed mathematically as (Deb, 2019):

$$\frac{\partial f(A)}{\partial A} > 0,$$

$$\text{but } \frac{\partial^2 f(A)}{\partial A} > 0$$

Therefore,

$$c = f(A).A$$

Where, A = store area
$f(A)$ = rate of conversion as a function of area

The conversion factor increases at a decreasing rate with increase in area. Therefore conversion factor can be expressed mathematically as:

$$f(A).A = \alpha.A^{\beta}$$

Where α, β are store specific constants:

$0 < \alpha \leq 1$ for conversion
$0 < \beta < 1$ considering decreasing returns to scale

Cost component again can be expanded into different sub components:

C_F = Fixed cost

C_O = Operating Cost, function of sales quantity

C_M = Maintenance cost, function of store area

r = Rent per unit area

Expanding the classical bid-rent model, the profit of the store is denoted in following equation 2.

$$\pi_i = p_i.a_i.f_i(A_i).A_i.g_i - [C_{Oi}.[a_i f_i(A_i).A_i.g_i] + r_i.A_i + CF_i + CM_i.A_i] \quad (2)$$

To relate rent and gate counts when other store specific variables remain constants, the above equation 2 has to be solved under the condition of maximizing profit

VGA and Agent Based Simulation

Virtual built space is adopted for analyzing foot fall (Reffat, 2008; Yan & Kalay, 2004) as it is a proven methodology for modeling human behavior (e.g. Franz, et al., 2005; Orellana &Al Sayed, 2013; Boustila, *et al.,* 2016). Four typologies are (e.g. Verdil, 2009) common for shopping mall layouts depending on the arrangement of circulation axes: Cartesian system, dumb-bell, branch or tree system and the hybrid system combining the elements of the other systems. Hypothetical layouts of equal leasable area have been prepared for the first three typologies. The Cartesian follows a grid network with one or more major arteries. Dumb-bell system has predominant central axis and two or more attractive spaces. The tree system, on the other hand, has a strong major axis with branching smaller axes from it. The hybrid one is eliminated from the analysis for presence of property of any two or all of the typologies. Three different mall typologies as identified earlier were created in drawing exchange format (*.dxf) considering equal total leasable and common circulation area (Figure 1). The layouts show mall interior public spaces without focusing on individual shop interiors.

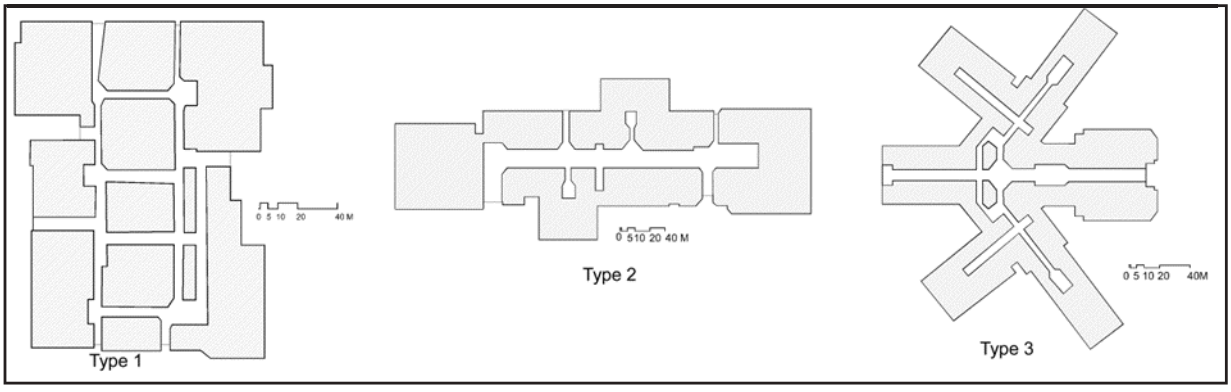

Fig. 1: Three Mall Typologies of Equal Leasable and Movement Area. From left, Type 1 (Cartesian), Type 2 (Dumbbell), and Type 3 (Tree)

The depthmap X software tool (Turner, 2007; Varoudis, 2012) has been used for VGA and agent based simulation in this paper for the above mentioned layouts by filling the layouts with grids (300X300 mm^2). The VGA generates values of TV and MMSPA for center point of every grid. The agents were released randomly from any random starting points within the layout following a standard movement rule (Turner, 2007). The standard movement rule of Turner (2007) recommended 170^0 field of vision for agents and three steps are considered before any turn. The agent release rate is fixed at 0.1 per timestep. The results of the simulation with standard movement rules correlates well with natural movement patterns in built spaces (Al_Sayed & Turner, 2012). The simulation result is done for 500 agents for all the above cases. The simulation generates gate counts for every center point of the grids along with values of through Vision (TV) and Metric mean Shortest Path Angle (MMSPA) value among others.

EXPERIMENT AND RESULT

The relationship between Gate Counts and Total Rent from a store

The profit earned from a store in a shopping mall can be derived from the bid-rent equation. By suppressing the

subscripts of the profit function of a store as expressed in equation (2) for ease of calculation it becomes:

$$\pi = p, a, f(A), A, g - C_0, a, f(A). A.g - r, A - C_F - C_M. A \quad (3)$$

For maximization of profit function, the first -order derivative of equation 3 with respect to A has to be zero, or,

$$\frac{d\pi}{dA} = a.f(A).A.g[p - C_O] - r - C_M + A.[a.g.\frac{df}{dA}(p - C_o)] \quad (4)$$

Again, in a condition of perfect competition, profits are negated by increment in rent, so that π=0. The Equation (3) yields:

$$\pi = 0 = a.f(A).A.g[p - C_O] - r.A - C_F - C_M.A \quad (5)$$

From the simultaneous equations 4 and 5, we can solve for optimum store area (A^*):

$$A^* = \left[\frac{C_F}{a.g.(p - C_O).\alpha.(1 - \beta)}\right]^{\frac{1}{\beta}} \quad (6)$$

And optimal rent r^*

$$r^* = C_F\frac{\beta}{1 - \beta}.[a.g.(p - C_O).\alpha.\frac{1 - \beta}{C_F}]^{\frac{1}{\beta}} - C_M$$

$$r^* = C_F\frac{\beta}{1 - \beta}./A^* - C_M \quad (7)$$

The total revenue from a store will be area multiplied by rent:

$$R = C_F\left(\frac{\beta}{1 - \beta}\right) - C_M.(\frac{C_F}{a.g.(p - C_O).\alpha.(1 - \beta)})^{\frac{1}{\beta}} \quad (8)$$

Total optimum revenue generated from a store under the condition of profit maximization can therefore be presented in terms of gate counts or foot fall under condition of ceteris paribus.

Figure 2 expresses the relationship between optimum revenue generated from a store in a shopping mall in terms of generated foot-fall at that store when other factors remain constants. It is clear from the mathematical expressions that, at g=0 the profit function becomes undetermined and the same happens for value of g at f'(g)=0. Total possible foot-fall depends on the locational characteristics of the mall. Therefore, the points beyond that value of footfall are unattainable. It is clear from the visual analysis of the graph shown in Figure 2 that, the optimum total revenue falls drastically beyond a particular foot-fall value. That point can be designated as critical and any values lower than that would fail to achieve maximum profit.

Gate counts as a Function of Spatial Variables

After analyzing the layouts with Depthmap x software, VGA yields values for TV and MMSPA for center points of

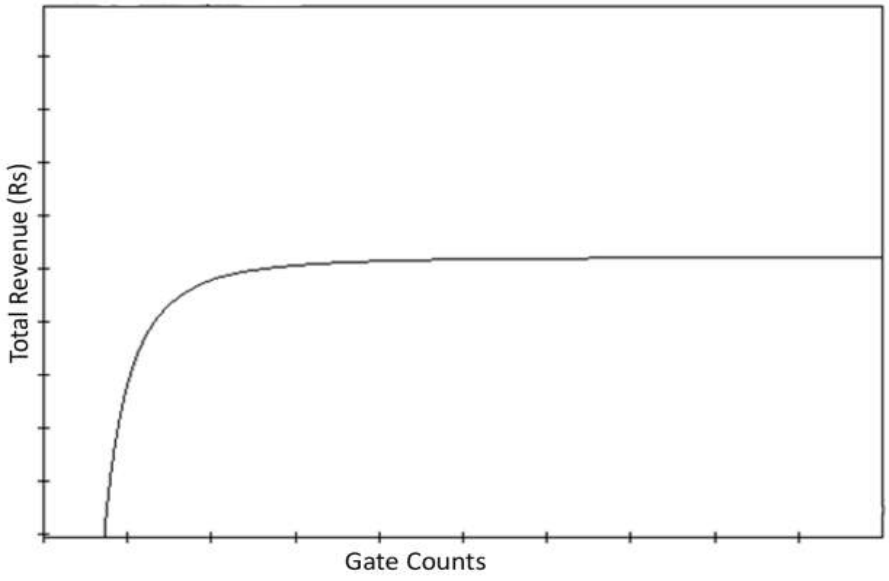

Fig. 2: Total Optimum Total Revenue from a Store with Respect to Foot Falls or Gate Counts under Condition of Ceteris Paribus from Equation 8

grids superimposed on the common area of circulation of the malls. Agent based simulation on the other hand generates foot fall or gate count values at those points of the corresponding layouts.

Figure 3 shows the scatter plot of gate count values from the simulations in terms of MMSPA and TV values for three mall typologies identified earlier. The scatter plot clearly exhibits that, gate count varies directly with TV values and inversely with MMSPA values for all the cases. The corresponding correlation coefficients are also significant. From the two sets of relationships it is inferred that gate-count is exhibited as a function of TV/MMSPA irrespective of the shopping mall typology. A transpose of square root of TV/MMSPA provides the best fit relationships (Figure 4) with gate counts where adjusted r^2 values for all three typologies yield satisfactory values (Chin, 1998; Hair, *et al.,* 2011) (Type 1: r^2*= 0.61*, Type 2: r^2*= 0.70,* Type 3: r^2*= 0.54).*

The constant and coefficient are highly significant ($p<0.001$) and the gate count or footfall can be expressed through spatial configuration variables as

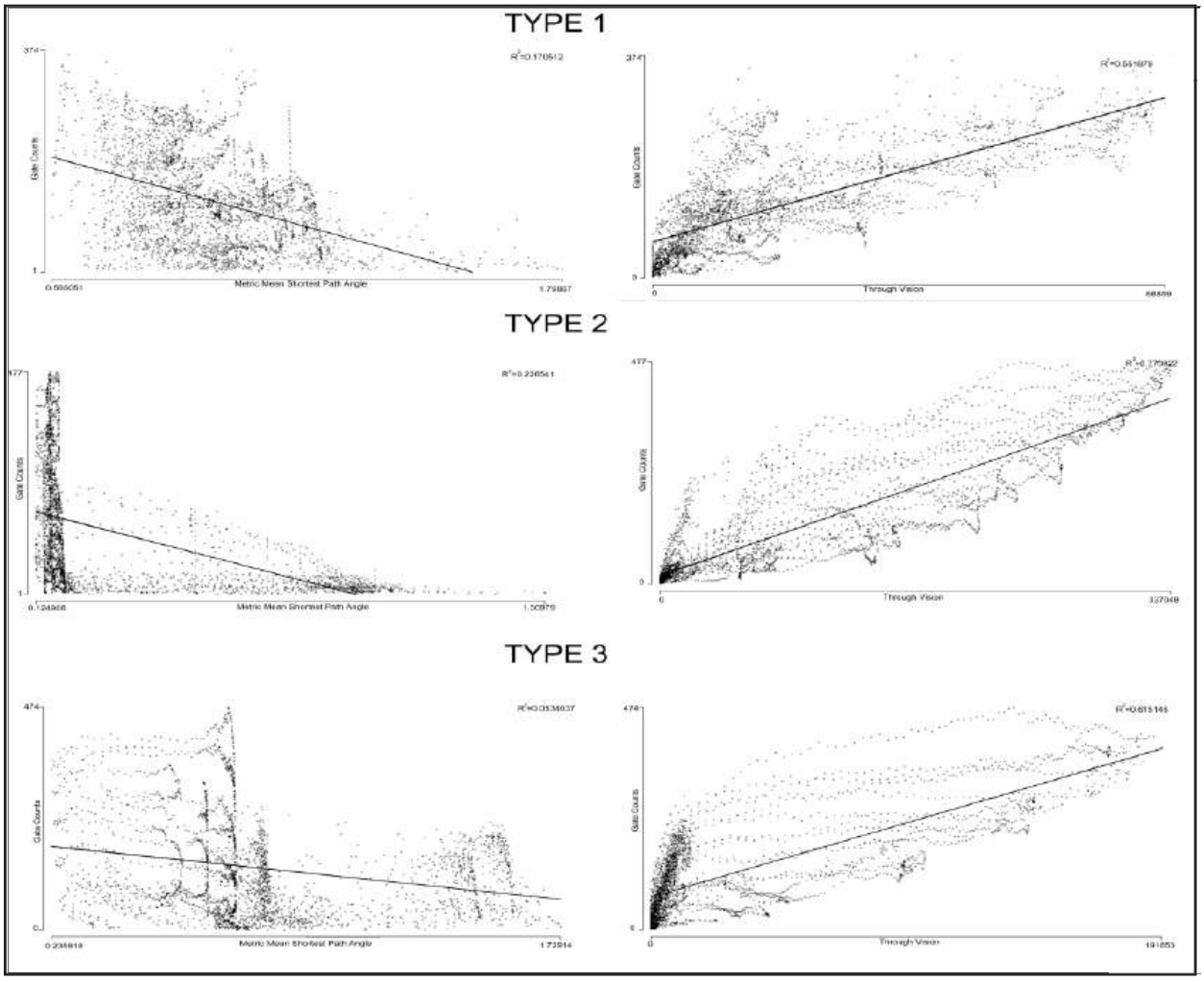

Fig. 3: Scatter Plot of Gate Count Values from the Agent Based Simulations in Terms of MMSPA and TV Values for the Three Mall Typologies Shown in Figure 1

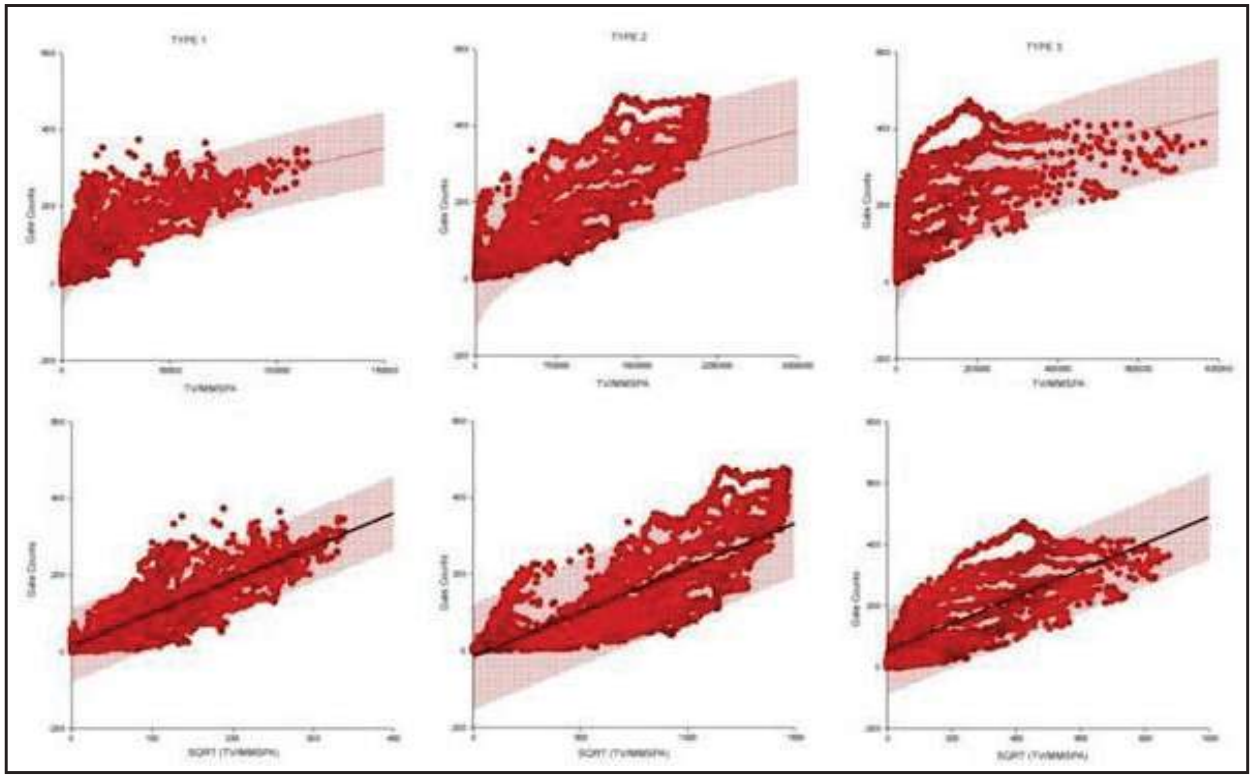

Fig. 4: Model Fit Analysis for the Relationship between Gate Counts and TV/MMSPA without (Above) and with Transpose (Below)

$$g = \gamma \sqrt{\frac{TV}{MMSPA}} + \delta$$

(γ= coefficient and δ= constant)

Eq. (9)

The gate count or foot-fall can therefore be expressed in terms of a simple functional relationship of configurational variables. The superiority of built environment in generating movement and resultant foot fall can therefore be easily established. Substituting the value of g in equation 8 will express revenue generation of a store in terms of spatial configurational variables.

FINDINGS

The revenue generation from a store of a shopping mall can be demonstrated in terms of foot fall and that, in turn, can be conveyed in terms of variables specifying configuration of built environment, TV and MMSPA. Undoubtedly, the revenue generation can be explained in terms of spatial configurational variables. Built environment is therefore not only an end in itself rather a potential tool for determining economic performance. The methodology adopted for visibility graph analysis makes the concept of strategic decision making difficult for implementation in practical cases. For operational effectiveness, the internal public spaces of the mall are decomposed in minimum possible non-overlapping convex spaces. The average values of configurational variables (TV and MMSPA) are considered for predicting foot fall in those convex spaces. The mechanism of decomposition of non-overlapping convex spaces is shown in Figure 5.

A conceptual framework can therefore be formulated for maximization of revenue for a shopping mall. A system is considered to have different number of zones. TV and MMSPA values for all the grid points will vary but δ and γ will remain same for the configuration. The process will start from the area of maximum gate counts. Best possible combinations of store type variables will be selected to maximize the revenue till the available leasable area around that convex space is allotted for lease. The process

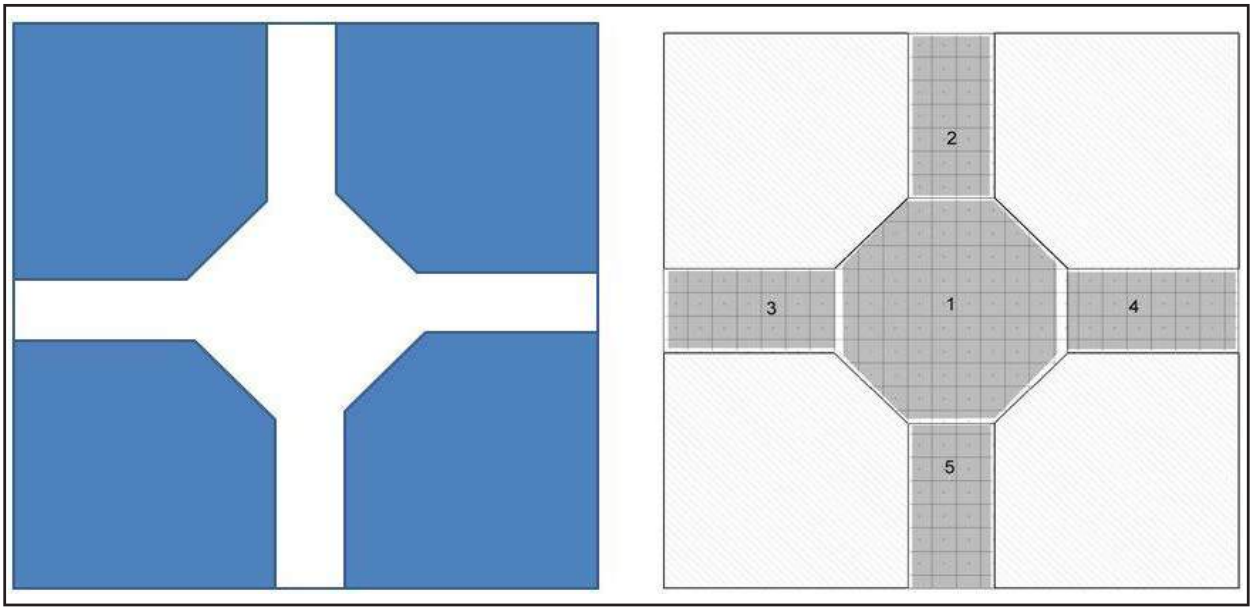

Fig. 5: The Mechanism of Decomposition of Internal Public Spaces of a Shopping Mall (Left: shown in white) in Convex Spaces Containing Different Number of Grids for Visibility Graph Analysis (Right)

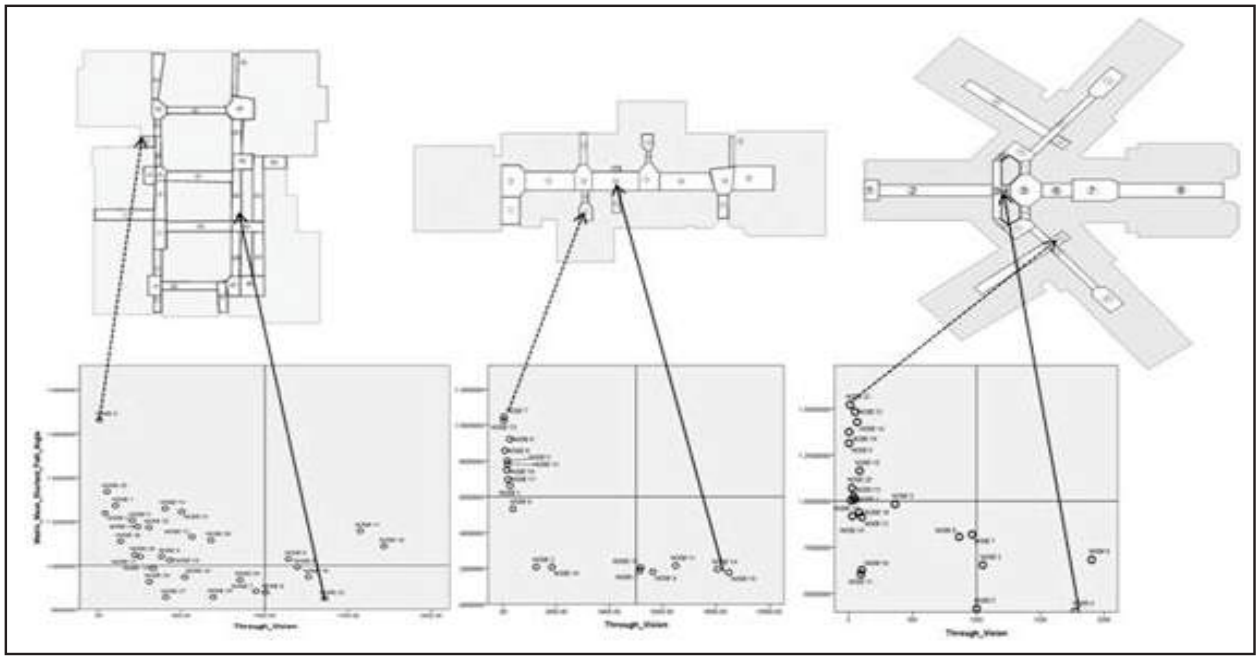

Fig. 6: The Highest and Lowest Foot Fall Convex Spaces for the Three Mall Typologies.

is repeated till the entire leasable area is occupied following the order of convex spaces in descending order of foot falls. The convex spaces with highest and lowest foot fall values for the three mall typologies are shown in Figure 6.

The iteration process of tenanting decision making will start from the convex space of highest foot-fall and will end at the lowest. The store specific variable values have to be ascertained at each convex space to allocate stores

around them. Tenant-mix will therefore depend on spatial configurational variables.

CONCLUSIONS

Current practices in the field of mall management treat tenanting decision making on a purely subjective manner. The location and area allocation decisions undoubtedly have spatial implications but the knowledge of built environment is mostly ignored in designing tenant-mix. Retail management acknowledged the importance of foot-fall in maximizing profit. On the other hand, researches in the field of architecture identify syntactical measures in influencing movement within a built environment. This research tries to bridge the gap between the two disciplines through integrating profitability of a shopping mall in terms of spatial configurational variables. Classical bid-rent analysis is resorted to establish the relationship between total revenue generation from a store in terms of gate-count or footfall. Foot fall, in turn, are expressed, in terms of spatial configurational variables, TV and MMSPA. TV is nonmetric or syntactic measure of configuration and MMSPA is a metric measure of configuration. This is another improvement from the retail research wisdom where metric distance is the only spatial variable considered for tenant –mix design. The optimum revenue from a shopping mall can be ascertained from the knowledge of spatial configuration variables. Space design is, therefore, not isolated from the decision making process rather an integral tool for influencing economic decisions like design of tenant mixes. The research result can be used as an evaluation tool for existing shopping mall as well as a generative tool for designing tenant-mix for greenfield ones.

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An Investigation into Visualization of Heritage Sites: A Case of Bai Harir Complex, Ahmedabad

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Abstract— The concept of heritage protection of monuments, sites, and precincts of significant cultural diversity is well practiced and evolved with various legal instruments. It has been recorded in traditional Indian culture, archaeology, antiquity, and monumental studies from the ancient past. In contemporary times, the various custodians are safeguarding the distinctive nature-based setting of monuments that evolve a blanket of the urban landscape. The context-based setting requires appropriate connections for monument sites and precincts with some control mechanism to ensure management and systematic future development. The paper aims to investigate visual parameters for site-specific settings with visibility analysis to regulate the heritage and its settings. In recent years, the draft heritage byelaws for protected monuments have been under preparation by various institutes and organizations. However, the volume of work is large, whereas the number of bylaws being prepared is limited and needs more effort from the ground reality. Additionally, these byelaws lack an objective approach to justify rich heritage knowledge through context-based assessments, guidelines, and recommendations. This paper justifies site-specific studies by visualizing culturally significant Monuments and their surroundings. Demonstration through visual simulation tools and the view control method would be applied to document the data. The paper discusses Ahmedabad city, India with a selected case study site under National Monument Authority (NMA) categorization as per the provisions of the Ancient Monuments and Archaeological Sites and Remains (Amendment and Validation) Act, 2010. Site-specific decisions can ensure the richness of Indian cultural heritage by prescribing the limits of prohibited and regulated (100 and 200 mts) areas around a monument and protected area. These areas are also referred to as the proximity and setting of monuments. This paper indicates the monument, Bai Harir complex, Ahmedabad, under category 7, in urban/ semi-urban limits. Further, it addresses existing findings by implementing a view control approach and visibility analysis as a visual assessment method via photographs, mapping, and geographic information systems.

Keywords: Monument and sites, Byelaws, Visual Assessment, View Control, Site-specific Settings, Visibility Analysis.

INTRODUCTION

A heritage monument or precinct's setting is an area that may have an impact in question but is not particularly valuable or significant in and of itself. The International Council on Monuments and Sites (ICOMOS) hosted its 15th General Assembly and Scientific Symposium in October 2005 in Xi'an, China. The "setting" theme is taken as its

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main focus and the setting is referred to as an immediate and extended environment. The Xi'an declaration recognizes that heritage buildings derive significance and distinctive character from their meaningful relationships of physical, visual, spiritual, setting, and cultural context. The declaration stresses the modifications and changes in development, as it carries the significant layer of the past and its culture. The monument and its setting should be managed to retain cultural significance by proactively leading modern development in historic locations (ICOMOS, 2005). The monument's surrounding is characterized by its vision from a certain distance as a symbolic meaning to the neighborhood, town, or city (Haddad *et al.,* 2022). There must be the prevention of monuments' significant settings from inappropriate visual (built form), encroachments, and land usage. Xian's statement during the ICOMOS meeting was particularly advised to consider, the monuments and their surroundings with significant skylines, sight lines, and adequate distance between any new public or private development (United Nations Educational, 2012). Historic buildings are important factors to consider while managing these cultural resources. Management of heritage sites and their settings involves various strategies that involve a value-based approach to protected or unprotected precincts or monuments (Ringbeck, 2008). The management of sites has become a crucial aspect of regulating urban development with a specific approach to contextual settings (Ababneh, 2016). Currently, India has around 3,695 national landmarks and heritage monuments (Ministry of Culture, 2013). These have varied surroundings and situations, with various challenges and issues. Rapid urbanization, harsh environmental conditions, visible pollution and careless development affect the heritage sites and their immediate neighborhood (Vishakha Kawathekar, 2020). Cultural sites are being neglected due to lack of suitable legal measures and enforcement, leading to careless interventions that disregard their setting and context (John, 2023). However, the settings are frequently populated places where the locals maintain a strong connection with the monument and play a vital role in sustaining its significance in society (Piatti & Martin, 2011). The association of locals recorded that there is very little empathy towards acknowledging the heritage and its landscape. Historic places such as Hampi and Golkonda Fort serve as a testament to the preservation of the heritage that the AMASR Act of 1958 enacted to regulate the development (Ancient Monuments and Archaeological Sites and Remains Act (AMASR), 1958). Before the 1958 Act, the protection of randomly known monuments of ancient, archaeological, historical, or artistic significance was declared under the 1904 Act as being of national importance (Ajay Khare, 2015). The 73rd and 74th Amendments brought the national law for built heritage protection Ancient Monuments and Archaeological Sites and Remains Act (AMASR) 1958 (Vishakha Kawathekar, 2020). The protection definitions of the act have been declared as ancient monuments, antiquity, and archaeological sites, and the remaining declaration analysis applies to those whose age is above “100 years” which recognizes protected areas in a restricted archaeological sense, declarative powers, and acquisition powers (Bernard Feilden, 2003).

A “monument” is a structure or object with historical, cultural, or symbolic significance (Bernard Feilden, 2003). It can be a physical structure, such as a building or statue, or intangible concepts related to culture and communities. The setting of a monument refers to its immediate surroundings and the context in which it is located (Corney & Payne, 2014). The setting plays a crucial role in establishing the relationship between the monument and the local community, integrating it into their lives (John, 2023). The preservation of the monument's setting is important to protect it from factors such as erosion, land development, and modernization (Basu *et al.,* 2013; ICOMOS, 2005). Under the AMSAR Act, the Archaeological Survey of India (ASI) is responsible for the protection and upkeep of nationally significant Indian monuments, sites, and antiquities (Publication of Notification of National Monuments Authority, 2011). Nevertheless, ASI's authority is limited to the border of the monument or precinct that the act designates as a "Notified Area," which may or may not have a memorial placed there. The "setting" around ASI-protected monuments and precincts is the subject of a new amendment to the AMASR Act (2010), which establishes a "Prohibited Area" of 100 meters and a "Regulated Area" of an additional 200 meters (with provisions for extending the restriction, if necessary). The Prohibited Area is off-limits to new construction, while in the regulated Area, monument-centric Heritage Byelaws shall govern development as initiated under the National Monument Authority (NMA) (Publication of Notification of National Monuments Authority, 2011).

The monument's heritage setting comprises a wide range of different contexts, including cultural sites, heritage sites, and historic urban landscapes (John, 2023). These settings are essential for comprehending the relationship between heritage and its stakeholders (Corney & Payne, 2014). With an emphasis on preserving and protecting the immediate environments of heritage places, the significance of settings in architecture, history, and archaeology has been acknowledged. The limits and thresholds of heritage

settings have also been included in the expansion of the idea of "place" (Bari, 2018). Griffiths, in his paper, suggested that the setting of heritage assets is just one specific aspect of consideration for assessing the impact of the proposed development, but it is relevant to all assets, whether world heritage sites, cities, monuments, or landscapes. (Griffiths, 2017) All heritage assets have a setting. One can manage heritage settings using the integrated participation from theory, conservation manual revision, and various policy measures (Fazan, 2023). Griffiths discusses the case studies from China, Italy, Malta, Turkey, and Peru with management practices in heritage settings. Explored the Management aspects (Griffiths, 2017) include financial resources, human resources, knowledge management, and relationships with the audience and scholars. Kalin & Yilmaz reviewed the effects of urban growth pressure on cultural world heritage assets and how the protection of heritage values is investigated with various comparisons of sites (Romo-Berlana *et al.,* 2023). Ababneh suggested effective management of cultural heritage sites through comprehensive urban development strategies to protect historic environments (Ababneh, 2016). The protection considerations of heritage assets and their settings can be regulated by framing a planning-based approach to the development around them. Sukwai investigated the landscape and terrain from the perspective of visual sensitivity to the cultural/ sacred sites (Sukwai *et al.,* 2022). Visual sensitivity is defined in the paper context as the capacity of heritage to maintain visual distinctiveness and signify the relationship with its surroundings. The visual sensibility assessment should contribute to the geographical landscape and monument setting. The suggestions are enquired through viewshed and skyline analysis considering the visual integrity of the mountain view corridor. The results showed that the buffer zone has more visual values and characteristics to the cultural landscapes from the view corridor of Chiang Mai's historic city. Therefore, the study argued that even low/medium-rise buildings that inappropriately appear in the horizontal visual plane could increase the sensitivity to this panoramic view (R. Zhang *et al.,* 2021). Zhang examined the visual analysis study of the inner spaces of monuments with deterioration risks to mural paintings studied by the visual analytics method that supports the risk management process (G. Zhang *et al.,* 2024). The assessment with graphs, charts, and maps is used to identify the pattern, color, and texture to develop action for protection led by data-driven decisions (Deufemia *et al.*, 2014). Introduced visual analytics to analyze and explain recent archaeological discoveries of large repositories of documents and drawings. The visual investigations for interpretations of new archaeological findings, detection of interpretation anomalies, and discovery of new insights. Qian experimented with a geo-visual analytics tool for archaeologists to analyze archaeological events (Qian *et al.,* 2016). Bari proposed a system for evaluating visual quality by combining visual features such as vistas, sense of place, visual absorption capacity, and aesthetic appeal with landscape character, assigning a high, medium, or low visual quality value to the landscape (Bari, 2018). Visions are subjective and impacted by personal interpretation, the outcomes will not be definitive. These visual cues can only be assessed based on established criteria and standards. Oťahel' assessed the visual quality of monuments from Bratislava city by evaluating the conditions of visibility of eight historical monuments based on multiple viewpoints surveyed and confirmed from a people-centric approach (Oťahel' *et al.,* 2018). The approach of viewpoint selection was subjectively and objectively identified. The method represented a comprehensive way of defining and verifying the places and ranking for effective sightseeing of city monuments from the urban study perspective. The visual clutter and proportion are the primary components to estimate visual impact. Keleş explains the visual character of natural and human-made artifacts and physical-biological sources (Keleş *et al.,* 2018). The physical presence of a historical landscape can be assessed with one of the approaches of the quality assessment method. Edirne City has experimented with conserving cultural resources with a planning-based approach. Tsuboi suggests, that urban landscapes are experienced by the people's perception of the built environment (Tsuboi *et al.,* 1979). The variables have been developed in the research with parameters like coherence, imageability, historicity, visual impressiveness, complexity, legibility, accessibility, security, inconsistency and city identity to approach and navigate based on the degree of visuality to the historic places. Sukwai explained the visually sensitive areas to be managed with the buffer zone identification (Sukwai *et al.,* 2022). The delineation of the buffer zone is of visual sensitivity values defending the view corridor concerning the regulation and recommendations. This method of viewshed and skyline analysis considers the pedestrian's visual limitation implemented in Chiang Mai City to produce the baseline for a built environment from an identified buffer zone to keep the built aesthetic harmonious in its cultural sense.

The methods for controlling views of significant cultural landmarks differ in various ways. Several approaches have been utilized to create methodologies applicable to context-specific circumstances in India. As recorded, this content-based research published is less in volume. The visual research studies for the monuments and their setting have not been approached from the conservation and planning

aspect in the Indian context. Therefore, research towards visual research studies is significant from a conservation and planning perspective.

METHOD

This paper includes an extensive literature review from peer-reviewed journals and a detailed examination of books, reports, and key legislative sources. The research observation and gap have been determined based on the current practices in the conservation domain from the visual research perspective (Thomas, 2021). The study of visual research is a multidiscipline domain where this paper also incorporates the historical perspective to enhance the quality of research with heritage site investigations. The study was conducted in Ahmedabad city with primary data collection on the Bai Harir complex. GIS thematic mapping, analytical tools, and ArcScene for 3D were used for conducting this research (Represented in Fig. 01). The visibility analysis demonstrated the efficacy of the Bai Harir complex as a national heritage site. This research is primarily structured with the qualitative approach.

SECONDARY STUDY

The literature review covered both primary and secondary sources, focusing on heritage and monument definitions, heritage settings, and legal instruments across India. It explored the heritage legal framework, as outlined in the conceptual theoretical framework in Figure 1, including the AMASR Act from 1958 to 2010, various charters and organizations, custodians of heritage protection and management, heritage schemes, policy interventions, and recommendations for urban development. It also examined planning theories related to historic cities and places, local, master, and regional plans, the Town and Country Planning Act, urban development guidelines, architecture and urban conservation books, and numerous research papers.

PRIMARY STUDY

The qualitative method was used to justify the selection of the heritage site and the historic potential of the city. The study was conducted in Ahmedabad city, Bai Harir complex using primary collected data. Visual simulation tools are used to evaluate the potential effects of the future building, which culminates in the creation of bylaws particular to each site and enabling design rules for new and infill construction, with the help of digital software programs like AutoCAD, GIS mapping, and Google SketchUp as mentioned in Fig. 1 under a proposed theoretical framework. Schematic drawings, photographic proof, visual simulations, and graphics have been created. The assessment tools from GIS thematic mapping have been used to demonstrate the results on the ground by using Viewshed and Visibility analysis considering the parameters like digital elevation modelling, building footprints, 3d model of the site area with ArcScene, and static view decisions as the view control method.

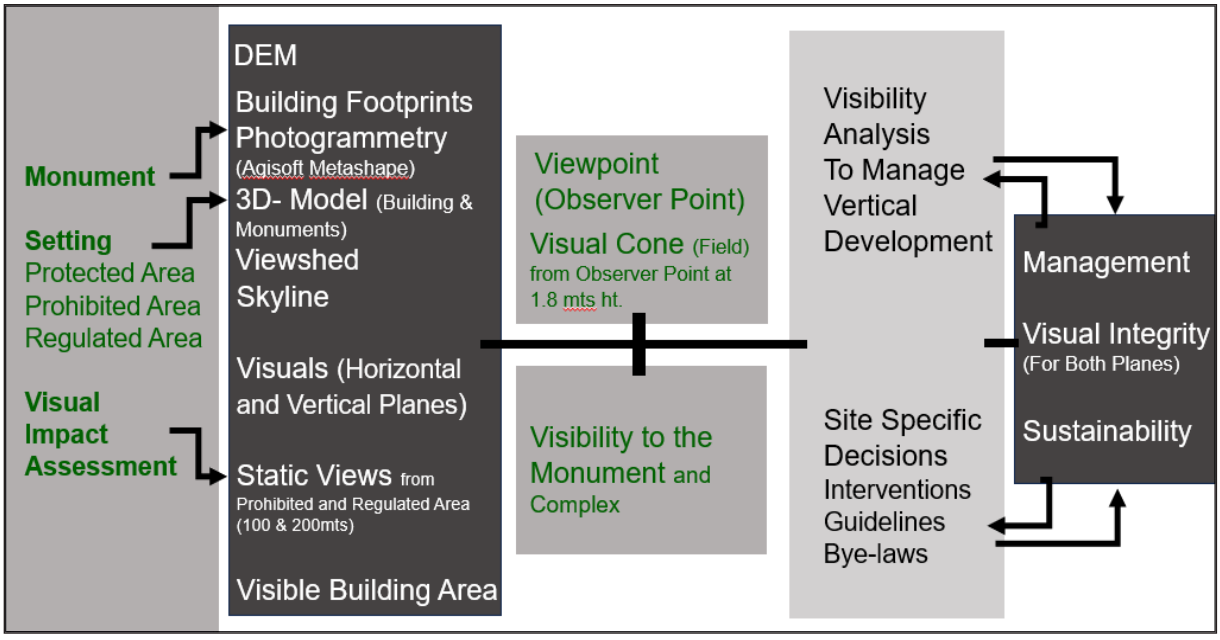

Fig. 1: Proposed Theoretical Framework

Proposed Framework

The research's methodological framework was created following a survey of the literature, current theories, and books on heritage, and how visual studies might improve understanding of the existing scenarios around the heritage sites. How does visibility analysis aid the visual assessment for site-specific decisions, guidelines, and heritage bylaws?

As in Fig. 1 under the Viewpoint considerations, the ArcGIS software's built-in analysis tools have been used to determine the 100 and 200 mts boundaries to decide for the static location of human height average of 1.8 mts. One fixed location (currently used roadway taken as the point of view consideration) from 300 mts to the monument complex and another from 100 mts taking the current approach road as a base for the degree of visibility to the monuments (Ancient Monuments and Archaeological Sites and Remains Act (AMASR), 1958). The degree of visibility in the study area with a static view cone is an attempt to analyze various layers like building height, skyline, and vertical and horizontal visual band visibility from the observer point. The analysis is framed with Viewshed and visibility analysis in ArcScene to visualize a 3-dimensional view of the study area with visual cone considerations. Moreover, Fig. 1 presents the theoretical framework that establishes the anticipated results and conclusions by addressing the primary study inquiry. How would this visual impact analysis assist in managing historic sites by incorporating contextual information and using planning to regulate contextual-based heritage bylaws? The results were demonstrated with GIS – Arch map-10.4 and ArcScene- 3d model- building height, using a spatial analyst tool- visibility analysis. The outcome determines the raster surface visible to the set of observer features or identified observer points with static location. How much raster surface is visible from the located observer points to validate the visual assessment of the heritage sites from 100 and 300 meters? The analysis will demonstrate the relevance of visual study to frame context-based (site-specific) urban development and sustainable management of heritage sites and their precincts.

CASE STUDY: BAI HARIR COMPLEX

Criteria for Selecting Heritage Site Changing of Horizontal and Vertical planes

The study area is rationalized by fulfilling multiple categorizations (listed by NMA) with a contextual setting that largely integrates Category-4, "Ticketed Monuments", Category-6, "Living Monuments", and Category-7, "Monuments in the urban/semi-urban limits" (Archaeological Survey of India, 2019). Bai Harir/Dada Hari stepwell and complex is defined with horizontal and Visual bands. The visibility in both directions (horizontal; Stepwell and vertical; Mosque and Tomb) from 100 mts and 300 mts (100 mts from monument protected area prohibited area, further 200 mts from prohibited area = Regulated area) as the linear expansion notified by AMASR (Amendment and Validation Act 2010). The case study of the Bai/Dada Harir complex is considered with static position and view cone visuality from prohibited and regulated limits to justify the visibility parameters. As shown in Figures 2,3,4, & 5, the complex has a 16th-century Stepwell (horizontal visual plane), Mosque, and Tomb (vertical visual plane. This heritage complex significantly makes the study relevant for visual research-based studies in conservation and planning with its historical, architectural, and cultural values for the effective management of heritage sites.

Approach to the Heritage Site

View control methods in heritage conservation refer to the techniques used to regulate the visible output of information resources to enhance how people perceive and interact with monuments and artworks. These methods aim to facilitate the interest of onlookers and provide a more conscious approach to heritage management processes. Eye-tracking research based on two static locations considered with the current approach road to the study area surroundings. The visibility is measured with a visual cone and visual cues are used to understand how observers look at reassembled historic places and objects during pedestrian movement. The proposed static view from a vertical height maximum was taken to illustrate the outcome of 1.8 mts as stated in Figure 1. View control methods provide visitors with a more immersive and engaging experience in heritage environments to be sensitized toward heritage and knowledge.

Bai/Dada Harir Complex Horizontal and Vertical Visual Band

Historically, Ahmedabad suburbs, created by Mehmood Beghda, expanded to the north of the city wall and were designated as haveli pargana (an administrative entity of many villages). Mehmood Beghda built a large territory outside the city wall. In the Haveli Pargana region, Dada Hari Ni Stepwell developed until eventually, settlement appeared and defined new boundaries for the Stepwell complex (Sriparvathy & Salahsha, 2021).

The existence of monuments that dated back to the Mehmood Beghda period and the Solanki dynasty. The complex includes a Step-well, a Mosque, and a Tomb. Figures 2, 3, & 4, present the significant architecture characterized by the Gujarat Sultanate style with an intricate blend of Hindu and Islamic carvings. Currently, the Stepwell serves as an ASI monument, and its surroundings (Asarwa area) are developed under the Town Planning Scheme (TPVD). The monument complex is centrally protected (AMASR Act) by the Archaeological Survey of India and was recently announced by NMA, as a monument categorized under semi-urban limits as explained in category 7. The complex is locally maintained under the supervision of (AMC) Ahmedabad Municipal Corporation. The AMASR Act of 2010 defines the monuments and their immediate surroundings with protected areas (complex/ precinct) 100 and 200 meters with prohibited and regulated areas respectively, in all directions from the monument-protected area (shown in Fig. 6). Fig. 2, defines the Bai Harir's complex protected, prohibited, and regulated areas with schematic vertical development of around 300mts. In the existing scenario in contemporary times, the complex is surrounded by various valuable other heritage components like temple trust and Gamthal Settlements.

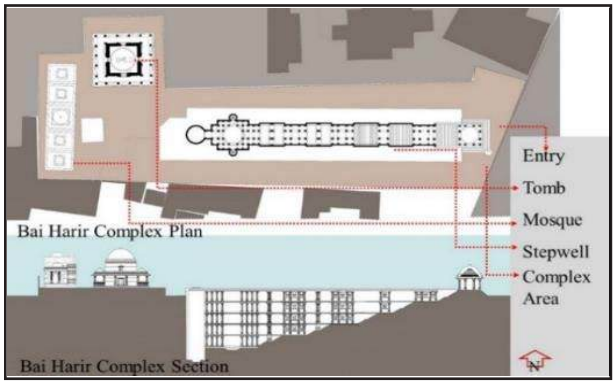

Fig. 2: Stepwell Complex Plan & Section

Fig. 3: View toward the Entry to Complex and Stepwell including Mosque and Tomb

Because of such other valuable heritage components, the complex and surroundings are culturally integrated from the past with religious and cultural activities. After the 19th century, the introduction of railways led to the development of the area with various fabric industries, godowns, coal yards, and other commercial areas that caused flux of migration, and eventually, informal settlements took place along the abandoned railway lines and compounds and coal yards currently used as the dumping yard.

Fig. 4: View of Mosque and Tomb from Stepwell

At present, Bai Harir and its setting are ignored due to high-density growth and a lack of ground-level implementations. This opposing condition of growth in an immediate setting of the prohibited area with coal yards, encroachments, and informal settlements obstructing the horizontal as well as the vertical views of the monuments. The precinct is polluted with chemical-based air pollution due to the coal godowns situated on the edge of the complex. Fig. 5, manifests the existing issues due to coal godowns, resulting as a direct threat to the heritage building material quality, color, and aesthetics. However, examining existing scenarios through visual integrity to the specific settings can be an effective approach, and this angle of study is yet to be experimented with. From the perspective of design, architecture, and planning, CEPT University, NIRMA University, and other institutes have conducted many scholarly investigations on this study area. From an Architectural perspective, one of the studio projects from CEPT University, India focused on the revival of the Bai Harir complex. After establishing other associative values within the complex, an interpretation centre has been proposed as part of an academic exercise. This approach was taken from a conservation-based perspective to understand the historical record of Char Bagh Garden (Vyas & Patel, 2021). Another approach looked at transforming the urban development pressure to create a sustainable hub within Bai Harir Stepwell with the integration of open and built spaces as the harmonious blend of past and present with varied living experiences. Various Academic research contributing to the studies of Sound,

Senses, and design principles have been explored for this case. The visual study of the complex and its surroundings is unique and significant research that has not been recorded yet from conservation framework aspects.

Fig. 5: Mosque and Tomb view from Godown Adjacent to the Complex Wall

The complex prohibited and regulated areas are effectively approached with visual analysis to safeguard the monuments and their specific settings. This shared living urban heritage can also be acknowledged by proposing site and context-specific bylaws. Since the eleventh century, the Dada Hari complex historic site has been a culturally significant account. As this complex developed with above and below-ground construction techniques the visual band and its integrity are regulated from some specific view in present times to control the view as the symbol and landmark of the Asarwa. The coal yard obstructs the view of the mosque and tomb, leaving only the dome visible when viewed from the storage buildings, as shown in Fig. 5. The area has undergone extensive construction, with unauthorized development exceeding 6 meters vertically, as illustrated in Fig. 6, along with schematic sections of the immediate surroundings at distances of 100 and 300 meters. The coal yard and the trucks parked along the main approach road turned out to be an unsafe environment for the visitors. Therefore, more on-site research is needed to raise awareness among local communities and stakeholders, focusing on visual research to help preserve and manage important heritage sites.

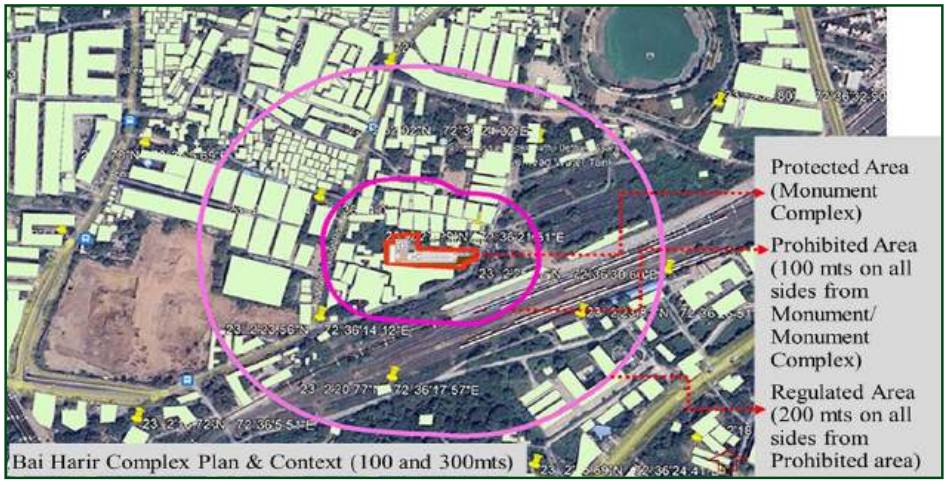

Fig. 6: Base Map with 100 and 300 mts area Demarcation (Protected, prohibited, and regulated area)

Fig. 7. & 8: Visibility Area Measurement from static stationed point (Observer location and height 1.8mts), Left: Observer location from prohibited area, right: Observer location from Regulated area

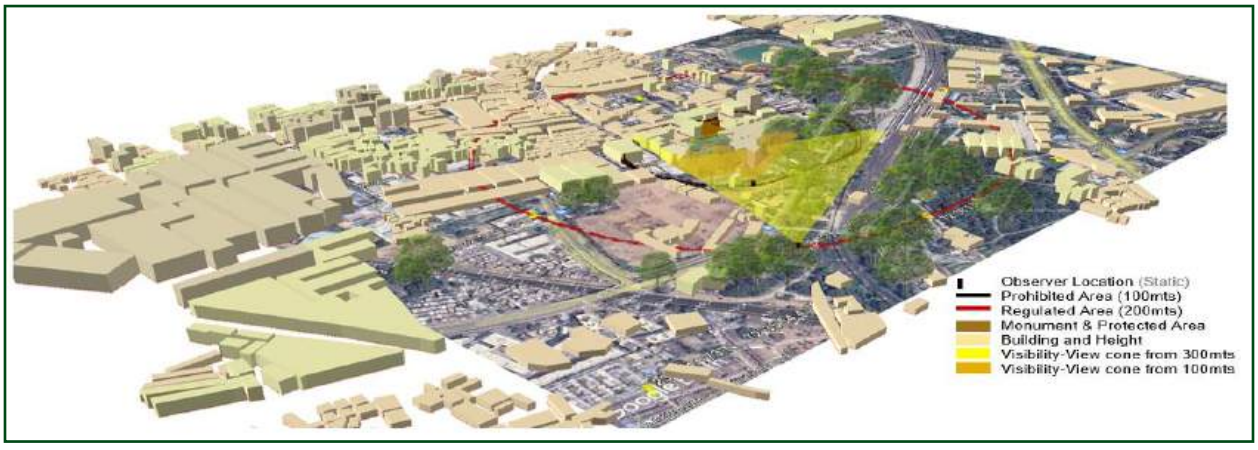

Fig. 9: Bai Harir Complex (Monument) Visibility Area Measurement in 3D Space from Prohibited and Regulated Area

Table 1. The Assessment Table for all the Analyzed Parameters based on Responsive Parameters

S. No.	Parameters	Bai Harir Complex
	(reference from AMASR, 2010 and Proposed by-laws, NMA)	Category 7: Monuments in the urban/semi-urban limits
1.	Vertical Visual Band	Yes
2.	Horizontal Visual Band	Yes
3.	Skyline	Needed
4.	Site Coherence	Needed
5.	View Control Points	02 (Static)
6.	Height, FAR & Setback	Needed
7.	Approach	Not Safe
8.	Addition & Alteration	Needed
9.	Relocation	Not Needed
10.	Public Amenities	Needed
11.	Signage & Direction	Needed
12.	Universal Access	Needed

RESULTS AND DISCUSSIONS

The paper discusses multiple visual studies, from building to urban domain, with multidisciplinary evaluations of monument settings. The literature study was conducted from local, national, and international case examples with multiple methods adopted for visual study. The analysis of this research aims to analyze the relevance of this study in a conservation-led planning approach. It also tries to answer the question, how can visual research through visibility analysis assist in regulating the conservation legislative framework for heritage sites and their contextual setting?

Visibility analysis is taken as a major objective to assess the existing scenario of the Dada Hari complex. The visibility analysis components were tested with ArcScene 10.4 Viewshed analysis and Visual cues analysis with static observations. The observation points controlled with the present approach road fixed at the vertical height of 1.8 as an average to view the complex from 100 and 300mts (results are shown in Figures 7, 8, & 9). Figures 7 & 8 explain the degree of visibility measurement from 100 and 300 mts (prohibited and regulated area), Archmap visibility analysis, represents the dark brown shade, which is not visible from the fixed point and vertical height, and the Redish -Pink color is the area which is visible from both static locations. The static location is decided based on the present road connection to the monument reach. The result has been recorded with the buffer, Viewshed analysis in 2D, observer locations, and 3D view planes as analyzed through figures 7, 8, and 9. Figures 7 and 8 represent the 2d visualization of space about the building heights and observer height from the distance of 100 and 300 Mts. The degree of vision reflected in the result, the heritage complex (monument and its complex) is almost visible from 100mts. As noted in the result from the viewshed analysis, from 300 mts visibility to the monument and complex is very low. It is difficult to navigate towards the heritage site without being visual. The immediate surroundings (unplanned development) obstruct the view of the tomb and mosque. ArcScene 10.4 is utilized in Fig. 9 to provide a three-dimensional understanding of the space concerning the fixed height and static location. Regarding the building heights, the ensuing result presents the same result in 3D space, and it is clear that the complex's aesthetic significance is being negatively impacted by

uncontrolled development. Viewshed and visibility analysis have been used to examine two approaches for visual impact assessment and visual band assessment. This may assist in managing vertical development specific to the heritage sites and their context. In heritage conservation, a policy-driven method can be applied in a context-specific way, using an integrated planning-led approach. Every historic site becomes a bridge between the past and the future. But who are these heritage places for, and to whom are they dedicated? Historic sites express their significance in various ways, through memory, experience, celebration, identity, politics, power, and more. Heritage sites should be preserved based on diagnosed sites' current values that can safeguard the future.

The Bai Harir site was examined from the visibility as the major concern to regulate area around the heritage sites for better development and content-based oriented. The paper tries to make an effort to highlight the debate concerning visibility both above and below ground from view control approaches. Visibility is one of the points notified by the NMA for making and proposing heritage byelaws, but there is no defined meaning of visibility, and the context of heritage sites is missing for such a study. To sustain the argument for a colossal skyline and visual band (as stated in Fig. 9 and Table 1.), this study attempts to show the extent to which the GIS- Archmap-10.4, Analyst tool using Viewshed and observer point for Visibility Analysis to examine the real-time context. The major parameters highlighted based on the literature and existing analysis are listed in Table 1. Depending on how contextual knowledge of monumental settings is understood, there may be additional dependent and independent variables. The topographical features, site setting, and geography are the main factors mentioned. The Bai Harir complex's current parameters, which were evaluated using the AMASR, 2010 Act as a guide, are presented in Table 1 and range from visual, skyline, view control point decisions, approach, placement of signage, and public facilities to universal access for a better overall experience.

Nevertheless, this study implemented contextual-based analysis through the utilization of visual assessment as a method for the effective management and protection of heritage sites, precincts, and their surroundings. The views in urban layers of settings are significant for the experience of the places by assuring the protection of cultural heritage and its settings.

CONCLUSION

The heritage precincts specify factors like the impact of height, mass, scale, coverage, Floor Area Ratio, setback, visual integrity, and visual experience to be regulated and guided through appropriate legal instructions that can be created from its context itself as listed in table 1. However, it is necessary to address the regulation based on the architecture, style, and construction specifics of the monuments and their settings considering stakeholders. The construction materials and obstacles concerning the immediate site context need to be addressed to regulate the heritage sites. Both the vision control methodology and visual simulations under specific circumstances of analyst thematic mapping, incorporating viewshed and visibility analysis, can be utilized to investigate the actual circumstances on the ground, as demonstrated in 3D Figure 9. The degree of visibility is identified from the located observer point above ground level (AGL) as the building heights near or adjacent to the Bai Harir Complex. This analysis concludes and helps decide the surroundings benchmark to control and protect the heritage complex. While some changes are not wholly unfavourable, they must be evaluated in light of how they will affect the monuments' significance and distinctive values in their specific environment. The visibility, visual integrity, the impact of height, building mass, and scale, among other site-specific factors contribute to the visual experience and have long-term effects that must be controlled and managed by a suitable regulatory framework. Transparency and an objective rationale approach are essential to establish communication between the legislative body, professionals, and locals for bringing change that is sympathetic and logical to the monuments' protection. The heritage guidelines and recommendations must be made with consideration of the setting of each monument and its unique value. This scenario exercises two significant skylines (above and below the ground) and the visual appeal of the monumental setting and its surroundings conducted with the Bai Harirs complex. The visuality is evident in the horizontal and vertical bands above and below the ground for a better experience and appreciation of the values. Factors like visibility allowed visual assessment by establishing view control methods by targeting the viewing area, view control study focused on observers' view cone established in the specific monument context.

The research study used in the semi-urban area of Ahmedabad city’s ASI- Category 6 Monument can enable

objectively to guide logically and methodically to frame heritage bylaws. It is necessary to critically understand the monumental precincts with their prohibited and regulated areas with sensitive approaches that can bring the cast in situ solutions to determine the values for coherent sustainable development.

CONFLICTS OF INTEREST

No conflict of interest was declared by the authors.

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Vernacular Settlement as the Smallest Unit in Sustainable Built Environment Research

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Abstract—The study of vernacular architecture is mostly focused on typology study, eco-friendly architecture, bioclimatic assessment, etc. with an aim to establish its stance on sustainable practices. The term sustainability is widely known; however, the term is more often used and understood in the context of the protection of the environment. The definition of sustainability or sustainable development is constantly evolving with an aim for more inclusivity. In the recent past, the definition of sustainability is being examined to include and represent various complexities of human society and its environment. The fundamental concept of sustainability revolves around preserving our resources for the benefit of future generations. This pertains not only to the environment, economy, and urban areas but also places significant emphasis on culture, which is increasingly acknowledged as a crucial component of sustainable development. Today, global institutions, scholars, and policymakers recognize the necessity of integrating cultural aspects or traditions into their strategies for sustainable development. This inclusion is considered vital in maintaining the stability of the other three pillars of sustainability. Vernacular settlements also referred to as traditional settlements, are renowned for their intricate symbiotic and interdependent dynamics. These settlements are not just environmentally sustainable but economically, socially, and culturally sustainable too. The research will explore this aspect of vernacular settlements through documentation such as settlement patterns, open space systems, the interaction of building typologies with the environment and social and traditional customs followed such as weddings, funerals, birth, and community festivals, and make an attempt to prove that the smallest unit of studying vernacular architecture through a qualitative and quantitative data analysis stating that sustainability should not be limited to eco-friendly typology or material but expand to include various facets of the community too for a more holistic and sustainable future.

Keywords: Vernacular Architecture, Settlement Planning, Culture, Housing, Sustainability

INTRODUCTION

History of settlement or settlement planning is studied across various fields of both science and social sciences to understand human relationship that led the foundation of various civilization of the world. Settlements provides a conducive base for a comfortable and safe living (Chen, Zhong, Li, 2023). However, with pressure of development and to cater to rising population, the definition of settlement in urban areas is now more often known as residential areas and dwelling units as accommodation categorising it into a physical unit with no or less social concept towards it.

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While peri-urban areas have become an extension of new ideas of residential development, rural areas have managed to remain more or less untouched with settlements and the various layers of relationship still intact. The core area of studies in research around settlement planning highlights the existence of various sustainable practices that exist to be able to draw lessons that can be further adopted by newer settlements or residential developments. These researches have also identified culture as one of the most important facets in retaining the value system that have managed to keep a number of sustainable practices alive till date.

While researches have continuously being highlighting the importance of settlement planning studies, vernacular architecture have been looked in isolation. Very few researches have not looked at vernacular architecture as part of a larger system. However, this is changing, the settlement study has gained a lot of momentum in various research field (Cusens *et al.* 2022). A study on spatial characteristics and influence mechanism of human settlement suitability by Chen, Zhong, Li (2023) highlights that while studies beginning to focus on human settlement suitability, most of these studies lack to study the underlying causes and influencing factors (Chen, Zhong, Li, 2023).

This study explores the gap in research of vernacular architecture as part of a larger system through a systematic keyword co-occurrent analysis using VosViewer and science direct database. The aim of the study is to draw attention to vernacular settlements and the various layers of systems that exist within it that ensures its sustainability both at ecology as well as social level through a study of selected traditional settlements of Northeast India. In this study we also highlight the disruption of social fabric of traditional settlements because of social housing policies. The VOSViewer analysis helps us in understanding research gaps that needs to be addressed for a more sustainable development policies and interventions as a way forward.

METHODOLOGY

This paper explores the critical role that settlement planning plays in the larger field of vernacular architecture research, highlighting the significance of comprehending historic settlement patterns by a thorough review of the literature. The goal of the study is to demonstrate how settlement planning influences vernacular architectural practices through an analysis of historical and cultural settings, with a focus on indigenous and culturally embedded communities. This study is a component of a larger PhD project that looks into the applicability of cultural studies to the planning and execution of social housing projects. The overarching objective of the project is to investigate how cultural elements might influence and enhance traditional settlement and how study of vernacular architecture should not be looked in isolation.

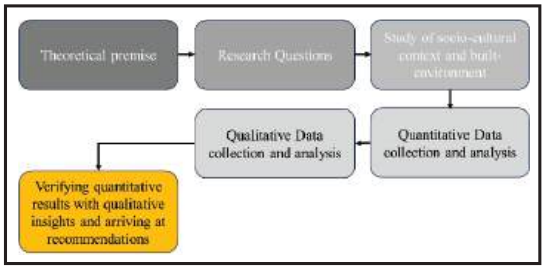


Fig. 1: Explanatory Researrch Design Flow

The research employs a mixed-methods approach, drawing on qualitative and quantitative techniques to obtain a comprehensive understanding of Assam and Manipur's vernacular settlements (as shown in Fig.1). While the quantitative technique may involve statistical data gathering, spatial analysis, and architectural surveys of existing vernacular structures, the qualitative part entails examining historical, social, and cultural impacts on settlement patterns. By combining these techniques, the study seeks to offer a comprehensive understanding of how regional cultural values, environmental factors, and social dynamics are reflected in and responded to through traditional settlement development. The purpose of this paper's conclusions is to aid in the creation of more inclusive settlement planning that are sensitive to cultural differences and uphold local customs while meeting modern developmeent demands.

Along with documentation of settlements, various activities, culture, and social construct were analysed as an integral part of the settlement. The research followed the following stages: (i) theories and concepts of traditional settlements were studied to highlight the sustainable systems of such settlements through literature study; (ii) a systematic keyword co-occurrence was conducted using VosViewer to understand the research focus in the field of vernacular architecture over the years; (iii) Vernacular settlements and systems of settings were explored through documentation of settlements; (iv) study of existing housing schemes and policies were studied and analysed to understand its impact on the socio-economic and built environment on the settlements.

RESEARCH FOCUS AND TREND IN VERNACULAR ARCHITECTURE

The focus of research in the field of vernacular architecture and sustainability lies mostly in the area of building performance and energy efficiency. This trend can be observed through the keyword concurrent map generated using VOSViewer. Keyword co-occurrence analysis helps the scientific research community to get an overview of various research trends especially to highlight the interdisciplinary linkages. Understanding and analysing the structure of the network helps research community to see thematic clusters or relevance of their own research across the global timeline.

Nodes in the keyword analysis represented by circles of various sizes and colours denotes a keyword that is extracted from the text. The size of the node represents the frequency of the keyword. Cluster or communities are represented by connecting nodes. Clusters highlight keywords that occur together more frequently. These clusters are a useful tool that can be used to understand research focus areas and the intensity of these research.

The keyword "Vernacular Architecture" and "Sustainability" were used from Science Direct database that gave a result of 831 papers that had the two keywords mentioned as shown in Figure 1. The keyword co-occurrence analysis was run using the RIS files downloaded. The network generated shows that research in and around the field of vernacular architecture is concentrated around the theme of thermal comfort, energy efficiency, sustainable architecture etc.

The cluster around "sustainability" shows keywords such as culture, conservation, heritage etc. Thermal comfort has a node size similar to the node size of vernacular architecture and sustainability highlighting the focus of research of vernacular architecture satisfying the three pillars of sustainability. Settlement planning or settlement on the other hand still hasn't made its way into the vernacular architecture and sustainability research in an impactful way.

Settlements and community living has played a critical role in the evolution of civilization ensuring the needs of humans are met at each stage of this evolution and ensuring these needs are met in the future too. The liveability of settlements has found to be linked with well-being and quality of life of its inhabitants playing an important role in the development process (Settijanti, Defiana, Setyawan, et.al, 2014). Traditional settlement are settlements are formed by the people living in them through transfer of knowledge and wisdom handed over generations (Dayaratne, 2018). A number of these traditional settlements were formed with collective efforts of the community and not through an individual vision. As stated by Akbar (1988), almost all the built form in traditional settlements showed uniformity such as choice of building material, design aesthetics, orientation among others (Akbar, 1988).

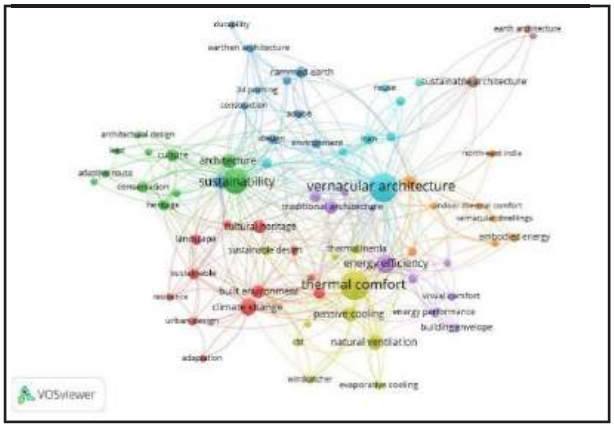


Fig. 2: Keyword Co-Occurrence Analysis of "Vernacular *(Source:* Map generated using *VOSviewer)*

Apart from individuals need to feel as a part of the community through various conformity of norms to the built form, traditional settlements have a number of cultural and societal norms that is followed by each household and individuals that leads to a systematic and sustainable functioning of the society as a whole. These systems and norms are what comes under "cultural sustainability" where development is balanced and inclusive even with various external influences (Sachs, 1999). As an example, during the time of demise of a member of the community, other households or members come together to support the family of the bereaved. Among the Meitei community of the Manipur of Northeast India, a system called "Shinyen Marup", which is a small sum of money collected from each household of the settlement to pay for the wood used during cremation. A male member from almost every household takes part in the process of cremation. Similar customs exist in some form or the other in different communities of Northeast India.

Traditional settlement's role in sustainability is not limited to environment responsive solutions but plays a key role in understanding the importance of social value systems that ensures collective community effort towards protection of the environment remains intact. Currently the focus of development around the theme of sustainability are towards newer technology that could provide environment friendly solutions, innovative building material and economic and affordable solutions (Dayaratne, 2018).

The concept of "home" can be examined from the perspectives of its relationship to the community it belongs to as well as the individuality it symbolizes. The premise that "home mirrors a wide variety of environmental and cultural influences" (Gauvain & Altman, 1982) is the dimension that the paper highlights. The issue of personality vs. society then comes up, and is it reasonable to believe that these effects will never be perfectly balanced? Even though their existence varies in degree, cultural influences—whether at the individual or social level—are an obvious fact. Therefore, it is assumed that the system is extremely dynamic and that it can have both short-term and long-term components. This study examines three general aspects of homes in different cultures: (i) façade and siting; (ii) thresholds and entranceways; and (iii) interior layouts and uses. The study, which drew conclusions from a variety of case studies from various geographical areas, was able to establish a significant influence in the built environment. Settlements in the kin-based hamlet of Tarong in the Philippines (Gauvain & Altman, 1982) built up their homes to guarantee social connection and the well-being of their members, as seen in one of the research's examples. The common area is maintained neatly and with pride by the inhabitants.

The research identifies areas in which housing and culture research could advance for a more methodical approach in this field that can be quantified and to understand how culture and families respond to typical life cycle changes, but it does not reach a conclusion on how or should culture influence the built environment. The study opens up a significant field of inquiry by emphasizing the requirement of comprehending the mechanisms influencing home design across cultural boundaries. A person's boundaries are defined as "self/other boundary mechanism that involves personalization or marking of a place or object, and communication that it is 'owned' by a person or a group" (Altman, 1975). This territorial model was adapted from various studies on animal ecology and human behaviour. Additionally, the necessity of property ownership is explained as a territorial behaviour (Sebba & Churchman, 1986).

DATA COLLECTION AND ANALYSIS

The case study area was chosen to encapsulate the intricacies of cultural context, since culture is defined as “a complex whole that includes knowledge transferred through generations, belief systems, laws, customs, and any other habits developed by humans as part of society” (Tylor, 2010) that influences society and settlement pattern. Two selected study areas concentrated on clusters of houses in a traditional settlement that further facilitated purposive sampling using a theory-driven approach to identify "manifestations of a theoretical construct to elaborate and analyze the construct and its variations" (Palinkas *et al.*, 2015). The survey was executed in one district of Manipur (Bishnupur) and one district of Assam (Baksa). A household survey questionnaire was created to gather data from the designated area.

Bishnupur was one of the three administrative divisions of the Manipur valley established in 1901; however, due to population expansion, Manipur comprised nine districts according to the 2011 Census of India. Bishnupur possesses a robust historical and cultural heritage, complemented with a distinctive topographical configuration that has influenced and characterized the constructed environment.

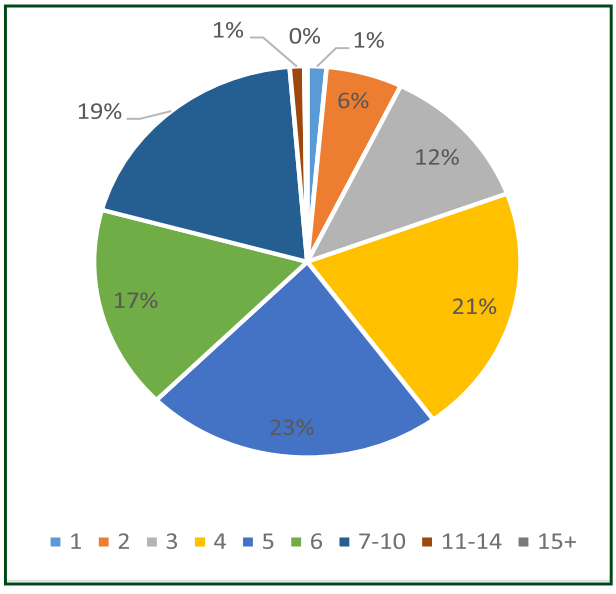


Fig. 3: Household Size Distribution of Bishnupur District (*Source* : Census 2011)

Historically, a significant portion of the area was governed by the "Moirang clan," one of the seven clans of the former Kingdom of Manipur. Bishnupur served as a significant cultural confluence in ancient times, functioning as a gateway for visitors entering or exiting the state through Cachar in Assam (District Census Handbook Bishnupur, 2011). According to the 2011 Census of India, the district's population is 2,373,999, constituting almost 12% of the state's total population, with a density of 821 individuals per square kilometer. Of the overall district population, 63.1% resides in rural areas. The district experienced a 13.9% decadal growth, the lowest among the state's

districts (District Census Handbook Bishnupur, 2011). The district comprises 46,413 homes, including 29,199 rural households (Census, 2011). The mean household size in the district's rural parts is 5.1.

Baksa is a district that was established in 2003 from four districts of Assam. The territory was governed by multiple monarchs, notably the British, as it was en route to the Northeast region. The district encompasses an area of 2400 square kilometers. Baksa shares an international boundary with Bhutan and features a gradual slope extending from the foothills of Bhutan to the Brahmaputra River basin. Several perennial rivers traverse the region to converge with the Brahmaputra River. The district is situated within the alluvial plains of the Brahmaputra River system and the River Manas sub-basin. The area comprises a combination of little hillocks and lowlands (Ground Water Information Booklet Baksa District, Assam, 2013). Baksa has a total population of 950,000, with 99% residing in rural areas. The district had a ten-year growth rate of 11% from 2001 to 2011. The region's ethnic composition includes Bodo, Rabha, and Garo, with Bodo constituting the predominant ethnic group in the district. The district has a significant Hindu population comprising 35%, while Muslims constitute a minor percentage. Scheduled Tribes comprise approximately 58% of the population, and Scheduled Castes constitute around 13% (District Census Handbook Baksa, 2011). The district comprises a total of 191,701 houses, with 189,249 located in rural areas. The mean household size in rural Baksa is 4.9 persons.

The research employed purposive selection to pick the panchayats, as the samples were distributed over a broad geographic area. This sample method is employed in qualitative research for the "identification and selection of information-rich cases pertinent to the phenomenon of interest" (Palinkas *et al.*, 2015), specifically regarding the influence of culture in traditional settlements. A purposive sampling employs an approach designed to "most likely yield appropriate and useful information while effectively utilizing limited research resources" (Bourgeault *et al.*, 2010). The sampling relies on evolving notions, specifically that housing units are a component of a system of settings that encompasses the entire community and settlement, with the objective to "explore the dimensional range or varied conditions along which the properties of concepts vary" (Campbell *et al.*, 2020).

The sample size was determined using Slovin's formula: $n = N / (1 + Ne^2)$, where "n" represents the sample size, "N" denotes the population size, and "e" signifies the permissible margin of error, set at 5%. A total of 225 households were surveyed throughout the four Panchayats.

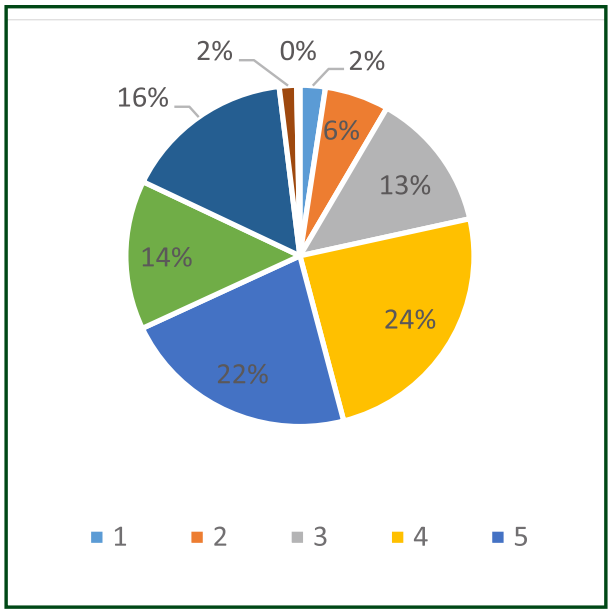


Fig. 4: Household Size Distribution of Baksa District (*Source :* Census 2011)

Table 1: Sample Size

State	District	Panchayat name	Sample size
Manipur	Bishnupur	Kha Thinungei	51
Assam	Baksa	Athiabari	174
The jamovi project (2012), jamovi. (Version 2.3) [Computer Software].			

The relationship between culture and the built environment that makes a traditional settlement a sustainable set-up is based on data sets derived from various questionnaire items that reflect culture in accordance with Amos Rapoport's definition: "the way of life of a people, including their ideals, norms, rules, routinized behaviors, etc." (Rapoport, 2005, Pg. 78). These items include (i) duration of settlement (ii) nature of support; (iii) nature of economic activity/income sources of family members; and (iv) cultural norms and regulations adhered to, if any.

The research employed a data triangulation strategy to utilize qualitative data gathered from the survey and professionals to corroborate the findings.

Table 2: Descriptive Statistics of "Culture" and "Built-Environment

Mean		
Variable	Bishnupur	Baksa
Culture	14.3	13.4
Built-environment	6.9	7.19
Standard Deviation		
Variable	Bishnupur	Baksa
Culture	1.18	1.31
Built-environment	1.71	1.55
Skewness		
Variable	Bishnupur	Baksa
Culture	-0.764	-0.639
Built-environment	-0.514	-0.728

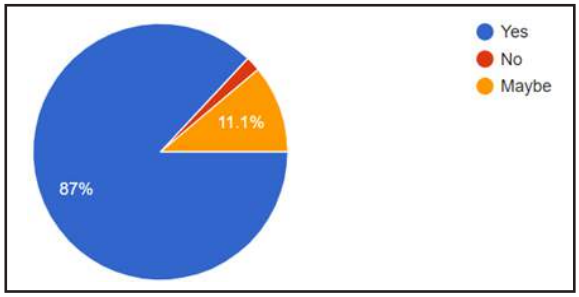
Table 3: Correlation Value

	Baksa	Bishnupur
Pearson's r	0.821	0.649
df	172	49
p-value	< .001	< .001
95% CI Upper	0.864	0.784
95% CI Lower	0.766	0.454

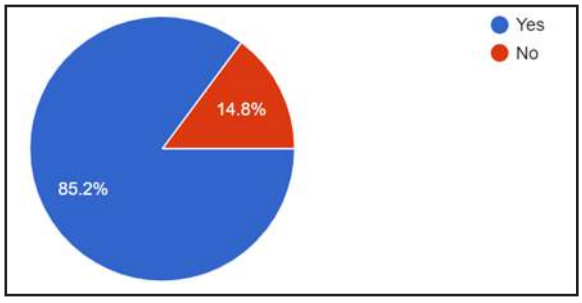
The data pertaining to "culture" and "built-environment" were analysed utilizing "Jamovi Project 2022, Version 2.3" [Computer Software] to conduct a correlation test employing the Pearson product-moment correlation coefficient. Pearson's correlation contains three assumptions: (i) both variables are regularly distributed; (ii) variables are measured at interval or ratio scales; and (iii) there exists a linear relationship between the variables (Schober and Schwarte, 2018). The coefficient values are emphasized in Table 3. Correlation analyses were conducted for the data obtained from the two districts.

While on the other hand, a concise questionnaire was distributed to 100 architects nationwide to ascertain their perspectives on the significance of cultural and traditional norms and to understand the its role in traditional settlements. This exercise was undertaken as nearly all architects participate in the design and construction of dwellings and are engaged in the entire process. They possess more awareness of the situational realities and must continually mediate between clients' requirements and practical, feasible solutions. The subsequent are the outcomes of some of the question:

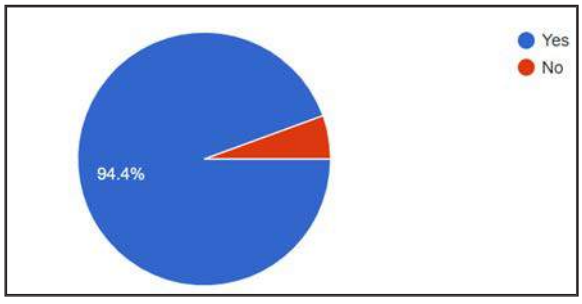
A. Do you follow any traditional norms or customary rules while designing a residence?



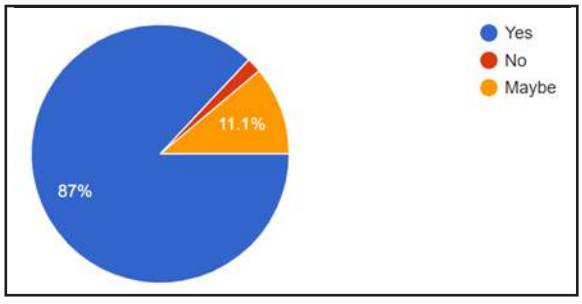
B. Do you think it is necessary to follow these traditional norms?



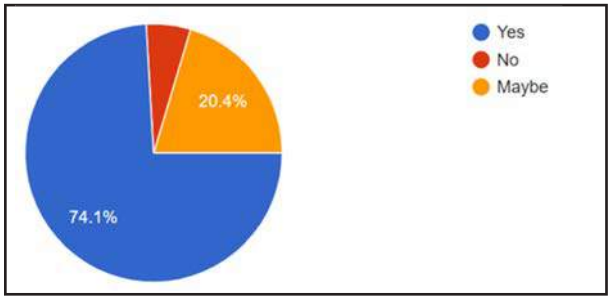
C. Should culture play any role in architectural practice?



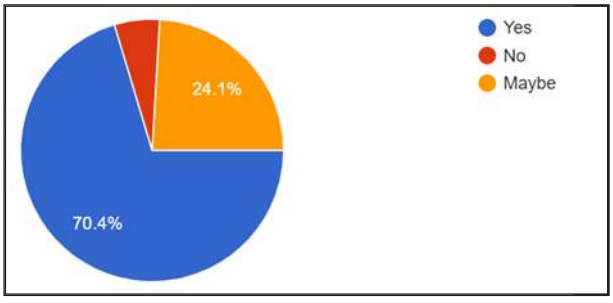
D. Do you think there is any science/rational behind the traditional norms that is followed in designing of a residence?



E. Do you think the traditional systems (not just building design but other day to day systems) were/are sustainable?



F. Do you think that the traditional building fabric encourages more community interaction than the current development system?



The data analysis indicated that culture affects human behaviour, which then modifies the built environment. The traditional system and environment significantly contributed to a sustainable ecosystem, wherein culture, closely tied to the value system, played a pivotal role. Engagement with professional architects indicated that numerous cultural norms and practices influencing the conventional built environment are underpinned by scientific principles or rationale, from which valuable insights might be derived. The notion of regarding culture as the fourth pillar of sustainability is significant in this context.

QUALITATIVE ANALYSIS

A well balanced built and open space ratio is a characteristic widely seen in many traditional settlements forming a sustainable community. Vernacular architecture and the settlement pattern's layout accommodated to not only cultural and religious activities but also to the day-to-day activity helping in generation of income along with daily functional needs of the household.

A typical Meitei settlement constitutes a well composed layout of open space network that is also used for various kind of activities and functions. The first level in this network of open space starts with a semi-open verandah infront of the house known as "mangol" in the local dialect. The concept of living room was non-existent in a traditional Meitei household, however the mangol served as the space where guest was entertained. Mangol find mentions in a book authored by British author R.Brown, F.R.O.S.E., a British documentation book of 1873 named "Native State of Manipur". In this book, the mangol is described as "a large open verandah, in which the family sits during the day, and in it all the work of the household is carried on, except cooking, which is performed inside; in the south side of the verandah is the seat of honor, here a mat or cloth is laid for the head of the family, upon which no one intrudes". Beyond this open verandah, was an open space with a "Tulsi plant" considered holy in Hindu culture. This open space called "shumang" was integral part of the built fabric where celebrations such as marriage, birth, funeral and other religious rite and festivals are celebrated.

Fig. 5: Traditional Settlement Fabric of a Meitei

Beyond the shumang on the eastern end of the plot, is a semi-covered platform with a roof on top facing the main house known as "shangoi". This place is used for weaving activity and other household activities. Traditionally, most houses had a rain fed pond in the front which caters to the water requirement of the households during dry season. Mangol is a private place while shumang which started as open space exclusive to a household became a shared space with increase of family size and married sons shifting out to start their individual households. However, the access to shumang is limited to the family.

A traditional Meitei settlement with several clusters of housing forms a community known as a "Leikai". A Leikai typically has about 15 to 50 clusters known as "kolup". A kolup consists of few households belonging to the same family. Depending on the number of dwelling units, the number of open space (shumang) can vary. Additional to shumang, there other kolup which have a temple and a semi-open space locally known as "Mantop" in front of the temple additional to the shumang. In terms of usage, while shumang is not shared between different kolups, Mantop on the other hand is allowed to be used by several kolups after

a request. These requests are mainly for functions such as marriage, funeral services, death anniversary etc. which are religious in nature. The Leikai (community) has a larger open space known as "Laimang" along with an adjoining temple dedicated to the Sylvan Gods or Goddesses. This community level open space was an integral part of the settlement and were used for community festivals, sports and as play areas. Laimang is an important social space that brought the community together through various activities. The built fabric of rural Assam stands almost the same in terms of relation of the dwelling unit to its open spaces, neighborhoods, economic extra. Dwelling unit do not function as a dwelling unit. It is an integral part of the environment that contributes to the day-to-day functioning of the household such as spaces of various economic and household activities, dedicated spaces for religious activities. The households in the settlement are known in each other and a number of social dependences exist within the community. Each house has a front court or open space that is used not only for functions and rituals but also used during harvesting season. Houses have dedicated space for a small temple in the open space, loom for weaving, storage area of grains, kitchen garden and animal rearing. The front verandah like the houses in Manipur are used for entertaining guest and for conduction various household activity.

Traditional settlements not only responded to the needs of the settlements in terms of community dependency and socio-political systems of the community but also responded to various space requirements for various activities which helped the community to sustain. Presence of open space, kitchen gardens, water bodies, weaving or grain storage space, sheds for animal rearing etc. makes traditional settlement an illustration of sustainable development of the four pillars.

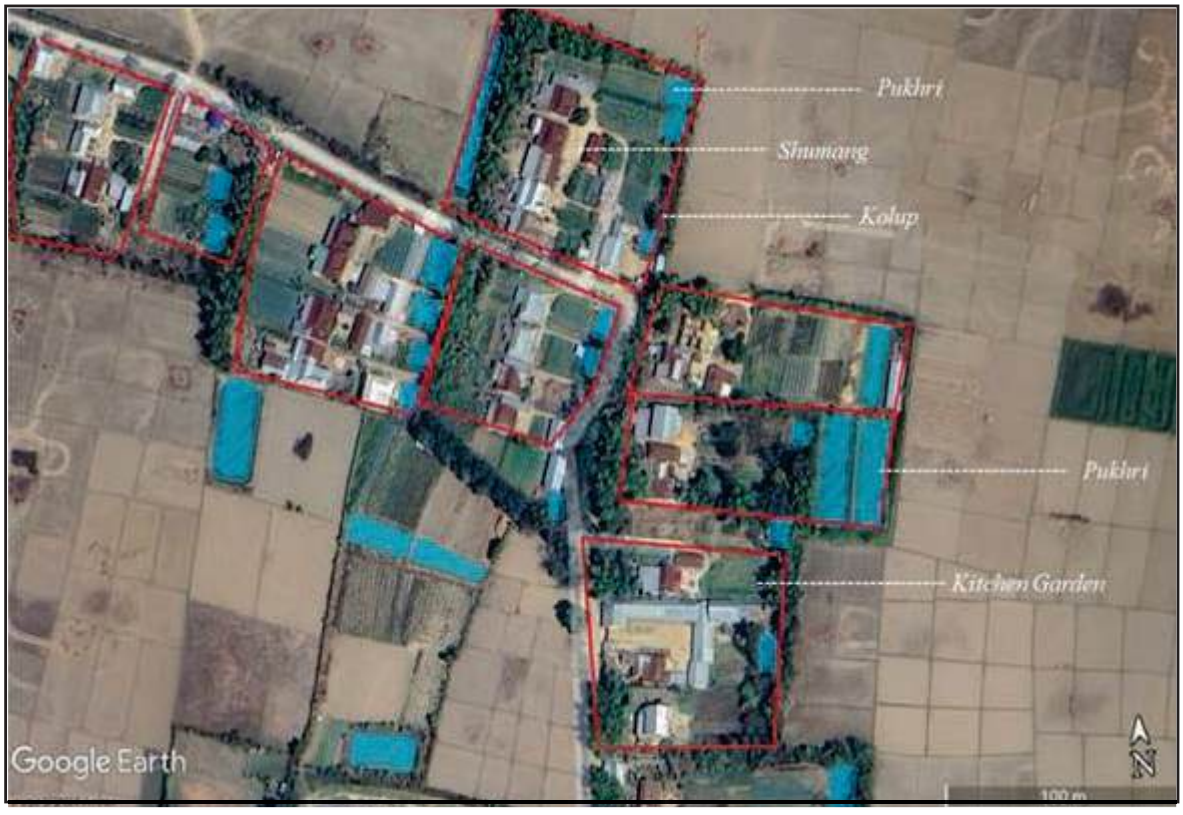


Fig. 6: Cluster of kolups in Rural Manipur (*Source:* Author)

DISCUSSION

Amos Rapoport (2005) in discussing the theory of "The Nature and Types of Environments" highlights the importance of interdependent empirical studies in the same way as how the study of buildings cannot be conducted in isolation (Rapoport, 2005). It further brings forth how "buildings relate as a part of system to open spaces, streets, other settings, neighborhoods, settlements, and sometimes even regions" (Rapoport, 2005). These system of settings as discussed in previous sections does not end with the dwelling unit itself but extends to both social as well as the physical environment.

During survey and interaction with households of Manipur and Assam, the question on, "Do u get support from neighbors and community in day-to-day life?", majority of the respondents answered yes in both Manipur and Assam. The nature of these support includes exchange or borrowing of household items, exchange of kitchen items, childcare support etc. Festivals and rituals including weddings and funerals were performed in the open space in front of the house. Almost all households had dedicated space for weaving, animal rearing and kitchen garden. The functioning of the household beyond the dwelling unit is captured in the survey of housing condition conducted in the 69th round 2012 under the "Micro-environment section". The working paper series on Rural Housing in India: Status and Policy Challenges for Lokshraya Foundationin 2016 highlighted the existence of some form of shed either attached or detached and constituted almost 62.1 percent of the households (Kumar, Deka, Sinha, 2016).

Veenhoven (2004) links happiness with quality of life. The quality of life is divided by two criteria in the form of a diagram as shown in Figure 4. where the vertical criteria are based on opportunities and life's achievement horizontal criteria are based on internal and external qualities (Veenhovan, 2004). Hence, through this matrix, livability is defined the environment which arise from both quality of life and external opportunities making the term reflect the characteristics of the environment (Setijanti, Defiana, Setyawan, et.al, 2014). A number of researchers argues that the quality of residential conditions of housing includes the characteristics of the environment in creating "an attractive residential neighborhoods" that includes both tangible and intangible aspects (Throsby, 2006 and Leby, JL and Hashin, AH, 2010).

Dwelling unit or household when looked at as an isolated unit falls short in representing the complex system of the society. A vernacular settlement uniqueness lies in the existence of various layers constituting both intangible and tangible elements. The sustainability of vernacular architecture will remain an incomplete study if the study isolates the dwelling unit from the settlement. The foundation of human behavior is the social value system and it is this value system that ensures that all members of the society is taken care of and also takes care of the environment at large.

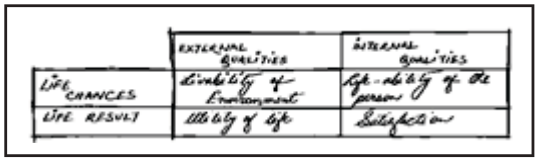


Fig. 7: Quality of life Matrix
(*Source* 1: Veenhoven R., Happiness as an aim in Public)

Indians view culture as an integral component of their own personal identity as well as the larger societal fabric, and they have a profound and nuanced grasp of it. They view culture as encompassing not only rituals and practices but also a person's relationship to their immediate environment, including their family, community, and environment, as well as their ties to the past. This past is viewed as a live component of present life, impacting beliefs, attitudes, and practices, rather than as something remote or unimportant. Indians also understand that culture is a dynamic process that must change with the times while holding fast to fundamental principles. Culture's ability to adapt lets it stay alive and relevant, allowing new influences and ideas to be assimilated without losing its core. This dynamic feature of culture demonstrates an understanding of the necessity for change, making traditions able to adapt to the demands of the modern world while maintaining their historical integrity.

Culture is frequently seen in Indian society as a reflection of one's standard of living. It includes social standards, values, music, literature, art, and language, all of which enhance the general wellbeing of the person and the community. A person's moral and intellectual standing are frequently deemed to be indicated by the breadth and depth of their cultural experiences. Therefore, a society's culture is evaluated based on how much it improves the lives of its citizens. Culture is ultimately the most valuable thing. It serves as a prism through which people evaluate both their own lives and the society they live in. It acts as a moral compass, teaching people how to coexist peacefully with the environment and other people. Thus, culture is viewed as "the ultimate value," essential to figuring out one's place in

the world, encouraging personal development, and creating a society that is fair and harmonious.

Change is an important element of culture and evolutionary process. These changes influenced by various external factors needs a strong policy backing as disappearance of many open system and traditional systems that made the environment sustainable have become redundant. The same can be said about vernacular settlement that unless it is not analyzed as the smallest unit of study in the field of settlement planning, architecture or rural development, the true essence of the vernacular architecture as a sustainable unit will remain ambiguous.

CONFLICT OF INTEREST

No potential conflict of interest was reported by the authors.

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Balancing Expert Vision and Public Desire: Reimagining Public Open Space for Lammual, Aizawl

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Abstract—This study delves into the complexities of urban planning in Lammual, Mizoram, by analyzing public and expert perspectives on public spaces and sustainable development. Our focus is on the often-divergent viewpoints on issues like traffic management, infrastructure needs, and the critical role of recreational spaces. A survey was conducted encompassing a diverse range of participants, including architects, engineers, urban planners, economists, and residents. Employing both open-ended and closed-ended questions, the survey gathers nuanced insights into land-use preferences, potential development options, and the unique needs of the community. The result reveal significant disparities between public opinion, which often reflects immediate concerns and desires, and the perspectives of experts who emphasize broader considerations of sustainability, inclusivity, and long-term urban development. Synthesizing these findings will provide valuable insights for policymakers, urban planners, and community stakeholders as they strive to create vibrant, inclusive, and most importantly, sustainable urban environments for Lammual and beyond.

Keywords: Public open spaces, Land use, Expert opinion, public participation.

INTRODUCTION

Streets and public places shape the character of a city. Public space shapes the appearance of a city, from squares and boulevards to community gardens and playgrounds for children. The network of open public space improves not only the quality of life but also the city's mobility and functionality. Well-designed and maintained streets and open public spaces can help reduce crime and violence, create space for formal and informal economic activities, and provide services and opportunities to a diverse range of users, particularly the most marginalised, for whom public space is 'the poor man's living room' and essential for recreation, social, cultural, and economic development.

Urban development is a multifaceted process that encompasses various dimensions, including social, environmental, and economic factors. At the heart of this process lies the creation and management of public spaces, which play a crucial role in fostering community well-being, promoting social interaction, and enhancing urban

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liveability. This literature review examines the benefits of well-designed and well-maintained public spaces, highlighting their contributions to social cohesion, physical and mental health, environmental sustainability, and economic prosperity. Drawing insights from diverse sources, including research studies, expert opinions, and case studies, this review provides a comprehensive understanding of the factors that contribute to high-quality public open spaces and the concept of publicness within urban environments. Through a case study on Lammual, we explore the divergent perspectives of the public and experts on urban development, shedding light on the complexities and challenges inherent in urban planning processes. By synthesizing these insights, this study seeks to inform policymakers, urban planners, and community stakeholders in their efforts to create vibrant, inclusive, and sustainable cities.

Public areas that can be used for physical and recreational activities, such as education and learning, benefit people' health and well-being. Public spaces that encourage active use benefit children and young people's physical activity as well as the sustainability of family life, particularly in green open areas. Public spaces should be viewed as chances for citizens to increase their access to the natural environment, so increasing their well-being. Parks and green spaces improve air quality while also providing residents with relaxation and leisure opportunities. Public spaces can also promote well-being and health by providing a network of public space that facilitates non-motorized transportation, such as walking and cycling. Public spaces with natural forested regions inside the urban landscape offer chances to encourage users to be more active, resulting in healthier communities (United Cities and Local Government, 2016).

Public spaces are the cornerstones of thriving communities, offering a wealth of benefits. They act as social hubs, bringing people together for interaction and community building. Events, festivals, and celebrations held in these spaces foster a sense of belonging and gemeinschaft, the German word for community spirit. Public spaces are also instrumental in promoting physical and mental health. They provide opportunities for physical activity through walking, jogging, and cycling, while green spaces with trees and nature have been shown to reduce stress, improve mental well-being, and enhance overall quality of life. Well-designed public spaces even contribute to a more sustainable environment. The presence of trees and plants helps purify the air and manage stormwater runoff, while also providing habitat for wildlife (UN Habitat, 2018).

Economically, public spaces can act as catalysts for growth. Attractive and well-designed spaces draw visitors, tourists, and businesses, leading to a more vibrant local economy. Businesses like cafes, restaurants, and shops flourish around these spaces, and property values in surrounding areas tend to rise, attracting further investment. Public spaces can also serve as platforms for cultural expression, showcasing the local talent and diversity through art installations, performances, exhibitions, concerts, and even outdoor film screenings.

However, creating high-quality public spaces goes beyond just aesthetics. Usability is a key factor. A truly successful space should be accessible to everyone, regardless of social background. It should reflect the local culture and offer a variety of activities that cater to a wide range of needs and preferences (Nasution & Zahrah, 2014). Function also plays a critical role. The space should serve the community's needs by providing opportunities for social interaction, recreation, and economic activity, fostering a sense of shared purpose.

The physical features and design of a public space also significantly impact its quality. Easy access through clear pedestrian linkages and integration with public transportation is crucial. The presence of trees, gardens, and a well-designed layout with appealing aesthetics all contribute to a space's usability and overall enjoyment. Regular maintenance is essential to ensure the space remains clean, safe, and the amenities function properly. Community involvement is a powerful tool in creating successful public spaces. When residents are involved in the planning and management process, the space is more likely to reflect their needs and preferences. This fosters a sense of ownership and responsibility, leading to a more vibrant and well-used public space (Nasution & Zahrah, 2014).

Publicness in public spaces is a multifaceted concept that goes beyond just physical accessibility. It's a complex idea influenced by historical, social, and cultural factors. Publicness encompasses aspects like accessibility for everyone, a sense of welcome and safety, and the embrace of diversity to accommodate a variety of people and activities. Effective management that considers rights of access, use, and control is also crucial for ensuring publicness remains intact (Li , 2022).

Challenges of Public Spaces in Hill Towns of India

Hill towns in India face unique challenges in the development and management of public spaces due to their topography,

fragile ecosystems, and rapid urbanization. Limited flat land, steep slopes, and environmental sensitivity make it difficult to create and maintain public spaces that are accessible, safe, and sustainable. As urban growth accelerates, overcrowding in these areas leads to overburdened infrastructure and unplanned development, further straining existing public spaces (Shekhar, 2018)(Dame *et al.,* 2019). Public spaces in hill towns are often poorly planned and maintained, with insufficient green areas, pedestrian walkways, and recreational facilities. This can contribute to environmental degradation, such as deforestation, soil erosion, and disruption of natural drainage patterns.

The fragile ecology and susceptibility to natural hazards, like landslides and flash floods, further complicate the development of resilient public spaces. In many cases, public spaces are neglected in favor of residential and commercial developments, leading to a lack of community areas that promote social interaction and cultural activities (Sharma *et al.*, 2024). Furthermore, public spaces in hill towns often lack inclusive design, limiting accessibility for the elderly, disabled, and children, due to steep terrain and inadequate infrastructure.

Public spaces in these towns are also vulnerable to environmental pollution, including air and water contamination, as well as the loss of biodiversity caused by unregulated development and tourism (Kaur & Garg, 2023). Inadequate planning and weak governance further exacerbate these issues. Small hill towns often struggle with limited economic resources, which impacts their ability to invest in sustainable, well-maintained public spaces that meet the needs of local communities (Shekhar, 2018).

Building regulations in hill towns are often outdated or insufficient to address the specific challenges posed by their unique landscapes. This leads to safety concerns in public spaces, with inadequate provisions for slope stability and environmental protection (Kumar, 2016). Aizawl Municipal Corporation (AMC) has introduced a slope modification clause to ensure safe construction, but enforcement remains difficult, which also affects the creation of stable public spaces (Aizawl Municipal Corporation, 2017). To promote sustainability, hill towns need a holistic approach to urban planning, emphasizing the development of safe, accessible, and environmentally sensitive public spaces that enhance quality of life for residents.

MATERIALS AND METHODS

This section describes the role of Lammual in the society and overall planning of the city.

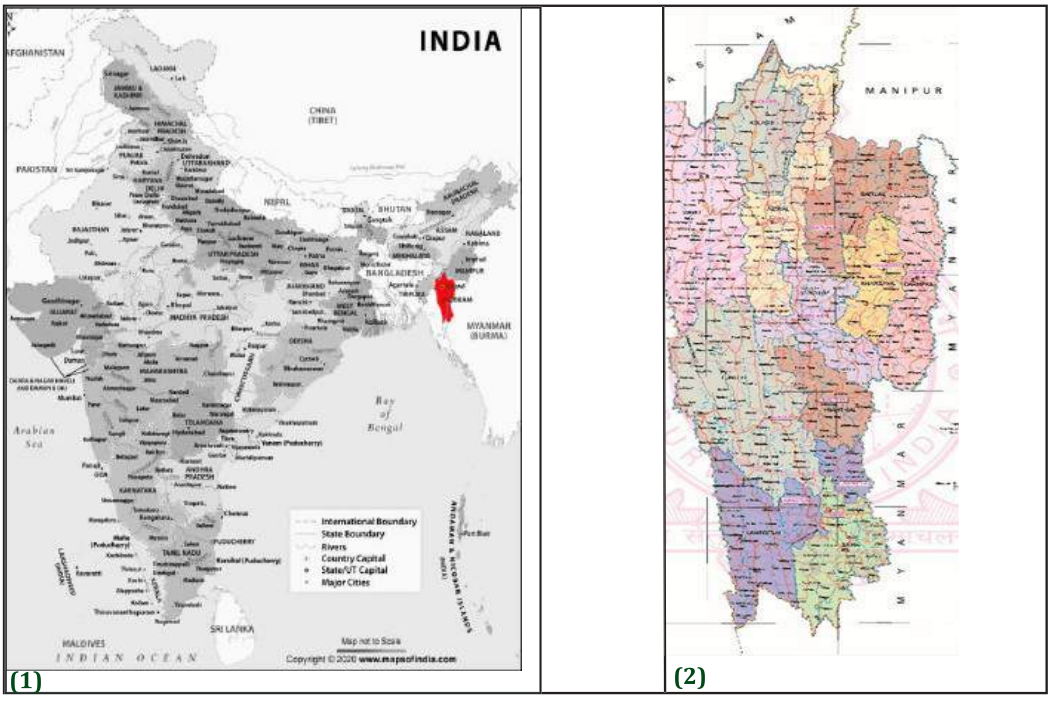

Fig. 1: Map of India showing Mizoram (*Source:* https://www.mapsofindia.com)
Fig. 2: Map of Mizoram showing Aizaw (*Source:* https://surveyofindia.gov.in)

Fig. 3: Aerial View of Aizawl City (*Source:* Google Earth as accessed on 21/06/2024)

Fig. 4: Lammual Stadium and Surroundings (*Source:* Googles Earth as accessed on 21/06/2024)

Study Area

Lammual, most commonly known as Lammual Stadium, is more than just a sporting arena in Aizawl, Mizoram. Aizawl is the capital city of the State of Mizoram which is located in the N-E part of India as shown in Figure 1 and Figure 2. Located in the heart of the city (Figure 3 and Figure 4).

Lammual transcends its function as a football pitch to become a vital center for Aizawl's social fabric. Lammual's central position makes it easily accessible to a large portion of Aizawl's residents. This accessibility fosters a sense of community, allowing people from various neighbourhoods to converge for events and activities. Lammual plays host to a multitude of social events beyond just football matches. The stadium serves as the venue for the vibrant Chapchar Kut festival, a major celebration of Mizo culture. Political rallies, public addresses by dignitaries, and other social gatherings frequently utilize the space, solidifying Lammual's role as a central stage for Aizawl's social life. The historical significance of Lammual further strengthens its social impact. The stadium witnessed the landing of the first helicopter in Mizoram in 1962, a landmark event marking the region's progress. Additionally, Lammual served as a platform for leaders like Jawaharlal Nehru to address the Mizo people in 1965, fostering a sense of national connection.

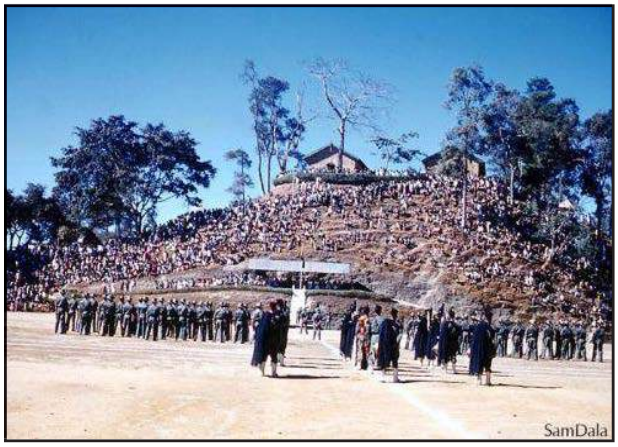

Fig. 5: Republic Day Celebration
(*Source:* Mizoram Tourism)

IMPORTANCE OF LAMMUAL IN TOWN PLANNING

Center of the City

The principal arterial thoroughfare of Aizawl extends longitudinally from east to west, with the Lammual precinct positioned centrally, serving as a pivotal nexus between Aizawl's eastern and western sectors. This strategic placement renders Lammual a focal point for vehicular and pedestrian transit, exerting a significant influence on the overall traffic dynamics of the city.

Fig. 6: Chapchar Kut Celebration
(*Source:* Mizoram Tourism)

Despite its development, Lammual lacks a distinct classification, as it neither qualifies as a commercial, recreational, nor residential zone. Surrounding Lammual are residential quarters to its east and west, commercial establishments to its north, and administrative facilities to its south. Consequently, Lammual remains devoid of a definitive identity, and any designation as commercial, recreational, residential, or administrative would not only redefine Lammual's character but also impact Aizawl's urban fabric. Given its strategic positioning and vast expanses of undeveloped land, Lammual holds the potential to either catalyse or hinder the city's progress.

Lungs of the City

Lammual stands as the solitary significant parcel of vacant land within the urban core, boasting a rich vegetation cover, earning it the moniker of the city's "lungs." Drawing parallels from international studies, such as those conducted in the United States, where urban forests have been shown to reduce building energy consumption by 7.2%, translating to an annual reduction of 43.8 million tonnes of CO2 emissions. Aligning with World Health Organization (WHO) recommendations, urban areas ideally require a minimum of 9 square meters of green space per capita to promote well-being. Discrepancies in green space provision are evident across Indian cities; for example, Chennai and Pune currently offer a mere 0.81 and 1.4 square meters per capita, respectively, falling significantly short of WHO standards. National-level guidelines, such as the Urban and Regional Development Plans Formulation and Implementation (URDPFI) Guidelines of 2014, advocate for a green cover ranging from 12% to 18% within urban areas. Various governmental policies, including the Ministry of Housing and Urban Affairs' (MoHUA) Urban Greening Guidelines of 2014, the National Mission for Green India (GIM) under the National Action Plan for Climate Change (NAPCC), and the National Clean Air Programme (NCAP), outline spatial norms for urban green coverage and delineate key stakeholders responsible for executing greening initiatives, encompassing eco-restoration efforts in both urban and peri-urban locales, as well as plantation schemes aimed at mitigating pollution concentrations (Climate centre for cities). As for Aizawl's current status, the specifics regarding its green coverage and compliance with these standards would necessitate a detailed assessment based on available data and local context.

Proximity Premium (Real Estate Value)

Several studies have corroborated the positive impact of proximity to parks, greenways, or recreational areas on property values, with increases ranging from 8% to 20%

compared to similar properties lacking such amenities, a phenomenon often termed as the "proximity premium." Even multifamily communities can experience a 4.9% uptick in property value when situated with views of forested open spaces. In 2021, a study commissioned by Outforia unveiled that, residences near Wyoming's Grand Teton National Park commanded values 389.94% higher than the state average. Furthermore, recent research highlighted by the Orlando Weekly indicates that theme parks, including all Disney resorts and Legoland parks, contribute to a proximity premium within a 10-to-20-mile radius. Additionally, strategic integration of natural elements like trees into green spaces or along streets can augment property values by 2% to 15%, enhancing the aesthetic appeal of both urban and rural settings while providing nature-based stress relief (Nowak *et al.,* 2016). Similarly, the incorporation of community gardens within parks or playgrounds can bolster property values, with homes within 1,000 feet of such gardens experiencing nearly a 10% increase in value over five years. Beyond financial benefits, community gardens serve as educational resources for children to learn about plant life and foster social interactions among residents, who can also enjoy freshly grown produce from these communal spaces (Lee , 2015).

With Aizawl City currently devoid of any significant public park which are easily accessible and inclusive. The prospect of a public space in the heart of the city seems verry much likely to change not only the real estate value but gave a whole new character to the area.

Mizoram's distinct topography, which consists mostly of steep hills and little flat area, creates significant obstacles for urban growth. Large buildable land parcels, like the one that Lammual currently occupies, are now scarce and precious due to this restriction. Any development on this property would have a significant impact on the infrastructure of the surrounding communities as well as the social, economic, and cultural landscape of the region.

Being a well-known hub of Aizawl, Lammual has the capacity to have a significant impact on how surrounding neighbourhoods develop and prosper. The patterns of mobility, social interaction, and economic activity in the neighborhood will probably depend on how this land is used, whether it is for housing, business, recreation, or a combination of uses. The choices taken here could have a ripple effect on future community development and urban planning in the city as the areas surrounding this site change.

Youngsters growing up in these communities are especially vulnerable to environmental changes. The environments people live in influence how they socialize, feel like they belong, and interact with the community. If Lammual is created with an emphasis on public places, community development, and inclusivity, it may inspire a generation that prioritizes the welfare of the group over the interests of the individual. Public spaces like parks, sports fields, cultural hubs, or common areas can foster community engagement and a feeling of purpose and identity among locals.

Lammual's importance extends beyond its monetary or property worth. It could turn into a representation of social integrity that strengthens bonds between individuals and promotes the transition to a more sustainable set of values. Development in this field should prioritize long-term social and environmental advantages over immediate financial gain. This would entail incorporating green areas, encouraging environmentally friendly building techniques, and making sure the development meets the requirements of the community as a whole.

Aizawl might have a more sustainable future if this change occurs, one in which urban growth improves community well-being rather than causing environmental damage or social disintegration. A more connected, sustainable, and peaceful urban environment in Mizoram may result from the deliberate renovation of Lammual, which may serve as an inspiration for similar initiatives throughout the city and surrounding area.

Public Space

There exists empirical evidence suggesting that green spaces exert a positive influence on stress physiology. Various Japanese studies have demonstrated the salutary effects of walking in forests and natural environments on physiological stress indicators, encompassing cortisol levels, pulse rate, blood pressure, and heart rate variability. Moreover, the quantity of green space has been correlated with favourable physiological stress regulation, as evidenced by diurnal daily cortisol patterns, particularly notable in underserved urban Scottish communities (Roe *et al.*, 2013)

Additionally, the classification of public spaces can be delineated based on gender dynamics. Social, religious, and cultural norms frequently dictate differential accessibility for men and women to various spaces. The absence of essential facilities catering to women further compounds this disparity, acting as a deterrent to their utilization of public spaces. This section will delve into these issues, exploring the divergent access patterns of men and women to the available public spaces within Aizawl city.

Public Space for Women

In many parts of the world, while women face no legal restrictions in accessing public spaces, social norms often deter them from certain areas. Women prefer marketplaces, cafes, and parks for leisure due to safety, comfort, and access to facilities. However, safety concerns, particularly during late hours, can hinder their mobility and limit their opportunities for education and work. Studies show women are willing to extend commutes for safer routes, highlighting the need for strategies against sexual harassment.

Men enjoy unrestricted access to public spaces, with women participating less frequently. In Aizawl, public spaces are often youth-centric, lacking amenities for women, children, and the elderly. Mizoram's parks, located on city outskirts, mainly attract young visitors, leaving families and older people underserved.

A centrally located park in Aizawl could address these gaps, providing a safe, inclusive environment for all demographics. Featuring playgrounds, well-lit paths, and seating for the elderly, it would encourage community interaction and healthier living. This space could foster inclusivity, offering a calm retreat for senior citizens and a welcoming place for families. Lammual, with careful development, has the potential to become a peaceful, social hub for diverse groups in the city.

CASE STUDY ON LAMMUAL

Expert Opinion *vrs* Public Opinion

The research framework was divided into multiple stages to systematically capture the varied perspectives on Lammual's land use and urban potential. This included the following key components:

Objective and Scope

The primary objective of the study was to gather insights from both professional experts and local residents regarding the optimal use and development of Lammual. The scope extended to investigating potential land-use designations (e.g., recreational, commercial, residential, or administrative) and evaluating their social, economic, and environmental impacts. Additionally, the study aimed to explore the implications of various development options on the city's urban fabric and the community's quality of life.

Survey Design and Implementation

A well-structured online survey was deployed from **20th February 2024 to 3rd March 2024,** targeting both expert professionals and members of the public. The survey was designed to:

- Capture qualitative and quantitative responses.
- Include a balanced mix of open-ended and close-ended questions.
- Address multiple thematic concerns such as environmental sustainability, urban mobility, social inclusivity, economic impacts, and heritage conservation.

Expert Panel

The expert panel consisted of architects, urban planners, engineers, economists, and sociologists, each providing a unique perspective on Lammual's potential:

- **Architects** contributed knowledge on sustainable building design and urban form, with a focus on green infrastructure and public space development.
- **Urban Planners** assessed land-use compatibility, zoning strategies, and long-term planning to enhance connectivity and functionality.
- **Economists** evaluated potential economic benefits, particularly the proximity premium and real estate value impacts of green space development.
- **Sociologists** explored social equity and inclusivity, addressing concerns around public space access for vulnerable groups, such as women, children, and the elderly.
- **Engineers** focused on technical infrastructure requirements, environmental sustainability, and ecological considerations.

Public Panel

The public panel consisted of local residents, community leaders, and other stakeholders, representing various demographics and social backgrounds. This group was integral to ensuring that the proposed development of Lammual resonated with local values and day-to-day practicalities.

- **Local residents** were asked about their preferences for Lammual's development, their current use of the space, and their concerns regarding access, safety, and inclusivity.

- **Community leaders** provided insights into the social cohesion and cultural relevance of the site, ensuring that any future development would support the communal identity.

Data Collection

The survey responses were collected and categorized into two main groups: Experts and Public. The Experts group made up 29.4% of the total responses, while the public group contributed 71.6%. Data was further stratified based on profession, age, gender, and geographic location within Aizawl to ensure a diverse representation of the city's population.

Data Analysis

The collected data was analyzed through both qualitative and quantitative methods:

- **Qualitative Analysis:** The open-ended responses were analyzed using thematic coding to identify common trends and concerns. This analysis helped uncover subjective opinions on land use, public space needs, and environmental impacts, particularly from the public group.
- **Quantitative Analysis:** The close-ended questions were analyzed using statistical methods to determine the distribution of preferences among various groups. Chi-square tests were conducted to identify significant differences between expert and public opinions on specific topics such as land use, green space provision, and urban mobility.

The findings from both qualitative and quantitative analyses were cross-referenced to highlight areas of convergence and divergence between expert recommendations and public sentiment.

INTEGRATION OF FINDINGS INTO URBAN PLANNING

The study culminated in the formulation of a holistic set of recommendations for the development of Lammual, balancing expert-driven insights with community priorities:

- **Convergence:** Areas where expert and public opinions aligned were prioritized, such as the need for more inclusive public spaces, increased green cover, and better urban mobility solutions.
- **Divergence:** In cases where opinions diverged, particularly regarding commercial development versus maintaining the space as a recreational zone, a multi-criteria decision-making framework was used to weigh the long-term social, environmental, and economic impacts of each option.

The results from this comprehensive case study were intended to guide urban planners and policymakers in making informed decisions regarding Lammual's development while ensuring that the process remains participatory and transparent

IMPLICATIONS FOR URBAN PLANNING IN AIZAWL

The case study findings not only provide a roadmap for Lammual's future but also set a precedent for participatory urban planning processes in Aizawl. The incorporation of public opinion alongside expert knowledge ensures that urban development is equitable, sustainable, and responsive to the unique needs of the local community. This approach can serve as a model for future urban development projects in Aizawl and beyond.

RESULT

Out of the 100 responses analyzed, 29.4% were classified as 'Experts' and 71.6% as 'Public,' as depicted in Figure 7. The 'Experts' group included professionals such as architects, planners, economists, sociologists, and engineers. These individuals contributed specialized knowledge from their respective fields. Architects offered insights into sustainable building and urban design, while planners focused on land use and long-term development strategies. Economists evaluated the economic impacts of sustainability initiatives, and sociologists provided an understanding of community dynamics and social cohesion. Engineers brought technical expertise on infrastructure and environmental systems. This expert input was complemented by the perspectives of the 'Public,' ensuring the sustainability indicators reflect both professional insights and local community values, making the tool more holistic and grounded in real-world priorities.

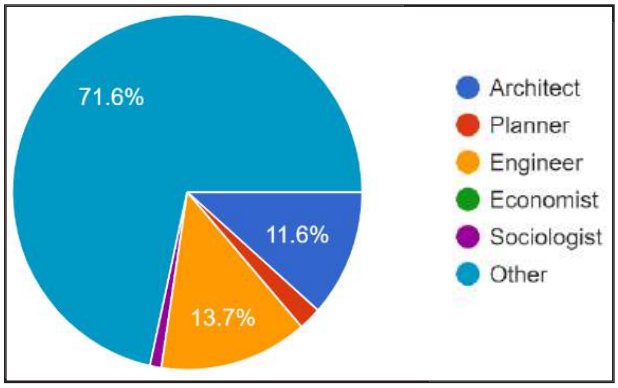

Fig. 7: Number of Responses

Discussion

From the public opinion, it's clear that there's a strong desire for the creation of green spaces within Aizawl, particularly in the densely populated neighbourhoods (Figure 8). The emphasis on undisturbed green sustainable parks and reserved plantation areas reflects concerns about air quality and the need for recreational spaces. Additionally, the call for affordable housing and a multi-purpose hall underscores the community's need for accessible amenities and spaces for various activities and events. The proposal for a recreational park in the city's core aligns with the public's desire for more leisure options and underscores the perceived lack of recreational areas. Moreover, the suggestion for a state-of-the-art shopping mall reflects a desire for modern amenities that cater to diverse needs and preferences. The emphasis on sports, especially football, suggests the importance of sports within the local culture. The call for a sports complex that can accommodate various events highlights the community's desire to preserve and enhance its sporting traditions while also providing modern facilities.

On the other hand, the expert opinion emphasizes sustainability and eco-friendly development (Figure 8). This aligns with global trends towards environmental conservation and reflects a more holistic approach to urban planning. The focus on creating an eco-park and green reserves underscores the importance of preserving natural habitats and mitigating environmental impacts. The concern raised about potential traffic influx due to multi-use spaces highlights the need for careful consideration of urban development plans and their potential implications. Balancing the need for amenities and recreational spaces with concerns about traffic congestion and urban sprawl is crucial for sustainable development.

Overall, while there may be some differences in emphasis between public opinion and expert opinion, both perspectives share common goals of enhancing liveability, promoting sustainability, and addressing the needs of the community. Finding a balance between these perspectives will be essential for effective urban planning in Aizawl.

The stark contrast between public and expert opinions on the Lammual development's potential to solve the traffic issue reveals a significant divergence in perceptions. While 38% of the public believes that Lammual development will alleviate traffic problems, a much higher percentage of experts (62%) express scepticism (Figure 9). This suggests that there is a lack of consensus between the general population and professionals regarding the effectiveness of this development in addressing traffic congestion.

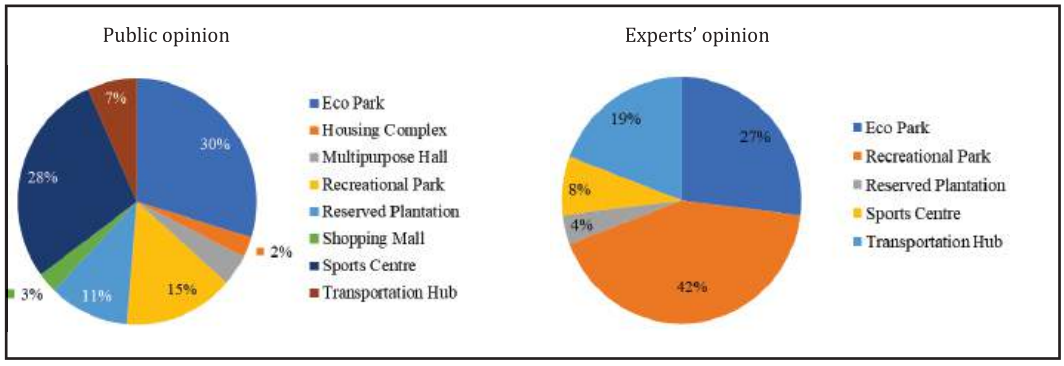

Fig. 8: Public *vs* Experts' opinion on type of development options

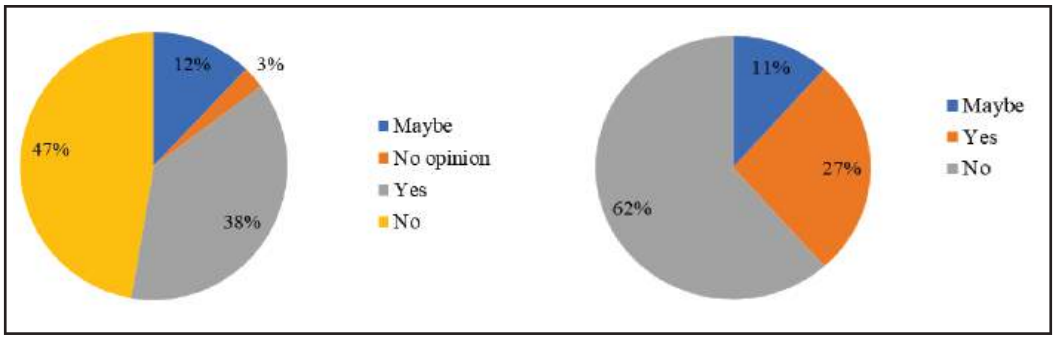

Fig. 9: Public *vs* Experts' opinion on – will Lammual Development solve traffic issue?

The disparity in opinions regarding the type of road—vehicular versus pedestrian—further illustrates differing priorities between the public and experts. The majority of the public (74%) prioritizes vehicular roads, indicating a strong preference for infrastructure that supports motorized transportation. In contrast, experts are evenly split (50-50) on the importance of vehicular versus pedestrian infrastructure, highlighting a more balanced perspective that considers both mobility and pedestrian-friendly urban design principles (Figure 10).

When it comes to the overall type of development, there is a closer alignment between public and expert opinions, with a slight preference for good infrastructure among both groups (Figure 11). However, it's noteworthy that a significant minority of both the public and experts prioritize recreational areas. This suggests that while infrastructure improvements are important, there is also recognition of the value of recreational spaces in enhancing the quality of urban life.

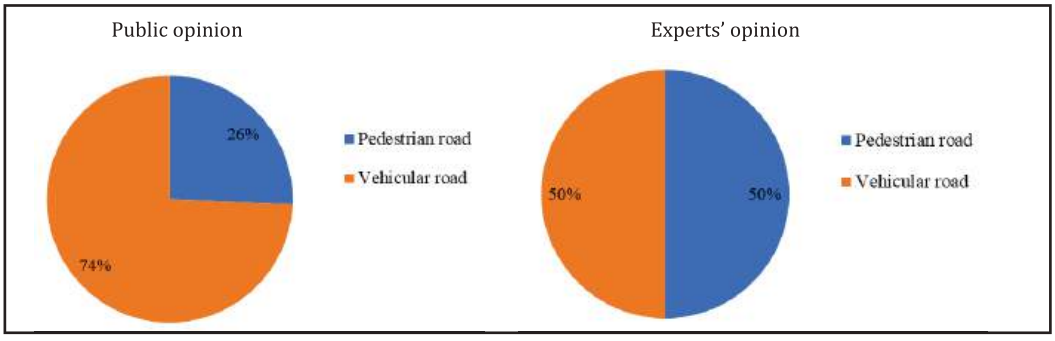

Fig.10: Public *vs* Experts' Opinion on Types of Road (Pedestrian or Vehicular)

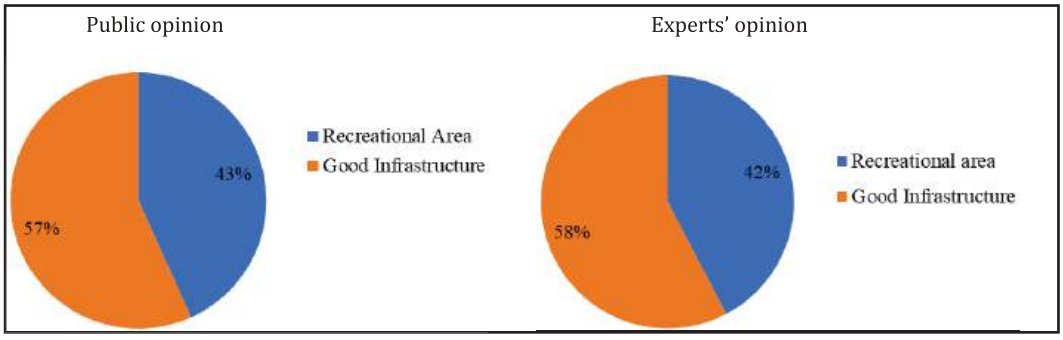

Fig.11: Public *vs* Experts' opinion on the two types of development

Overall, the discrepancies between public and expert opinions on these issues underscore the complexity of urban planning and the challenge of reconciling diverse interests and priorities. While the public may prioritize immediate concerns such as traffic congestion and infrastructure, experts bring a more nuanced understanding of urban development principles and long-term sustainability goals. Finding a balance between these perspectives will be crucial in designing effective and inclusive urban development strategies in Lammual.

Synthesis

Both experts and the public agree on the need for green spaces, though their motivations may differ as comments from Table 1. Experts focus on sustainability and strategic urban planning, while the public emphasizes immediate benefits like leisure, clean air, and social equity as shown in Table 2. In the discourse on urban development in Aizawl, both experts and the public underscore the need for green spaces, albeit for different reasons. Experts emphasize sustainability and the long-term strategic planning that prioritizes environmental health, urban resilience, and systematic growth. They view the development of an eco-park and reserved plantations as essential to channel Aizawl's growth towards sustainability. For instance, the eco-park would contribute to ecological balance and foster a sustainable urban framework, while a reserved plantation would preserve biodiversity and create green reserves within the urban fabric.

Conversely, the public focuses more on the immediate and practical benefits of green spaces, such as leisure, clean air, and equity. The public advocates for an eco-park that offers a much-needed green pocket within the city to improve air quality and provide a recreational space for all income groups. The emphasis is on creating accessible green areas that contribute to the community's well-being and serve as "lungs" for the densely populated city. This highlights a stronger desire among the public for spaces that fulfill immediate leisure needs and contribute to social equity.

Traffic congestion is another concern raised by both experts and the public, though their proposed solutions diverge. Experts propose relocating parking clusters and creating a transportation hub to streamline traffic flow. This reflects a technical, solution-oriented approach to the city's infrastructural needs. Meanwhile, the public calls for a transportation hub that centralizes all transport services, including a Maxi Cab terminal, which would not only address traffic issues but also offer a one-stop solution that improves daily commuting experiences for residents.

Recreational parks are also seen as vital by both groups, though experts warn of potential traffic influx, while the public stresses the absence of leisure spaces in Aizawl. Both groups agree on the value of a multi-use sports center, which reflects a shared interest in promoting physical health and sports, integral to Mizo culture.

The discussion highlights the necessity of a holistic approach to urban development in Lammual that balances sustainability, recreational needs, housing affordability, and traffic management. By integrating these diverse perspectives, city planners can create a multifunctional and inclusive space that meets the long-term needs of Aizawl's residents while promoting a healthier, more sustainable urban environment.

CONCLUSION

The comprehensive exploration of literature and empirical data on public spaces, health and well-being, factors contributing to high-quality public open spaces, and the concept of publicness within public spaces provides valuable insights into the multifaceted nature of urban development. These findings underscore the interconnectedness between

Table 1: Experts' Opinion on Type of Development

Expert Opinion	
Eco Park	An eco park channels towards sustainability, and this is the main reason why any form of development in this area has to go in this direction.
Recreational Park	Aizawl doesn't have a recreational park as of yet for leisure, which can act as a multi-use open plaza. Some also however mention that making it multi-use can increase traffic influx.
Reserved Plantation	For green reserve
Sports Centre	To grow in the field of Sports, a sports stadium which can also be used for other events.
Transportation Hub	Mainly to cater to the current traffic congestion in the area, by relocation of the existing parking clusters and addressing the demand

Table 2: Public Opinion on Type of Development

Public Opinion	
Eco Park	Aizawl has seen increase in densely packed neighborhood without provisions of green areas, except on the periphery. As such, an undisturbed green sustainable park is required to provide a place for leisure and green pocket to provide clean air in the core of the city.
Housing Complex	Govt backed housing which is affordable to tackle current soaring rents.
Multipurpose Hall	A multi-purpose hall to cater to events of varying functions.
Recreational Park	Aizawl largely lacks recreational areas, as such, a recreational park in the core of the city to accommodate leisurely activities catering to all age groups is the need of the hour. This will also act as the lung of the city providing clean air.
Reserved Plantation	Aizawl and its vicinity are lacking thick green reserves, a reserved plantation area is therefore required to act as a habitat to cater to multiple flora and fauna, while providing clean air. Reserved plantation in the core of the city is also likely the most equitable development that can be made for all income groups.
Shopping mall	Aizawl doesn't yet have a state of art shopping mall.
Sports Centre	The area has been largely associated with Sports, mainly football. As such, to upkeep the value of sports, which is innate amongst the Mizo people, a Sports complex, which can also cater to other events is required.
Transportation Hub	Transport hub which incorporates all transport offices, with ample parking space, which also act as Maxi Cab terminal to act as a one stop solution to tackle traffic problems in Aizawl

physical environments, social dynamics, and community well-being, emphasizing the importance of holistic approaches to urban planning. Through a case study on Lammual, we observed a divergence between public and expert opinions on various aspects of development, ranging from traffic management to the prioritization of infrastructure versus recreational spaces. While public opinion often reflects immediate concerns and preferences, expert perspectives offer a broader understanding of sustainability, inclusivity, and long-term urban development goals. The discrepancies between public and expert opinions highlight the complexity of urban planning processes and the importance of stakeholder engagement in decision-making. Finding a balance between immediate needs and long-term sustainability objectives is essential for creating vibrant, inclusive, and liveable urban spaces. Overall, this study underscores the importance of integrating diverse perspectives, data-driven analysis, and participatory approaches in urban planning processes. By leveraging the collective wisdom of both the public and experts, cities can develop innovative and sustainable solutions that address the evolving needs of communities while fostering social cohesion, environmental stewardship, and economic vitality.

RECOMMENDATIONS AND POLICY INTERVENTIONS FOR THE STUDY AREA

Here are some recommendations and policy interventions for the Lammual development:

Balancing Public and Expert Opinions

a) **Prioritize green spaces:** Develop a plan that incorporates green spaces like eco-parks and green reserves, catering to the public's desire for recreation and the expert's focus on sustainability.

b) **Mitigate traffic congestion:** Address traffic concerns through a mix of solutions informed by expert advice. This could involve improved public transportation, pedestrian infrastructure alongside limited vehicular access, and strategic road network planning.

c) **Find common ground on development type:** While good infrastructure is important, integrate recreational areas to fulfil the needs of both public and experts for a well-rounded development.

Public Engagement and Education

a) **Participatory planning:** Involve the community in the planning process through workshops, surveys, and public forums. This fosters transparency, addresses public concerns directly, and allows for incorporating local knowledge.

b) **Educational campaigns:** Educate the public about the long-term benefits of sustainable development practices and the potential drawbacks of prioritizing solely on short-term solutions like extensive vehicular access.

Specific Policy Interventions

a) **Land-use policies:** Implement policies that encourage the creation of mixed-use developments with affordable housing options, recreational areas, and green spaces.

b) **Traffic management policies:** Consider congestion pricing for vehicles, designated pedestrian zones, and investments in public transport infrastructure to reduce reliance on cars.

c) **Environmental sustainability policies:** Develop policies that promote energy-efficient buildings, green building practices, and renewable energy sources within the development.

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Data Availability: Data available on request due to privacy/ethical restrictions.

The data that support the findings of this study are available on request from the corresponding author, [E.R]. The data are not publicly available due to their containing information that could compromise the privacy of research participants.

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Climate-Responsive Architecture and Social Cohesion: The Role of the Verandah in Kutch's Traditional Dwellings

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Abstract—The verandah, a time-honored architectural space, has garnered substantial interest due to its adaptability across varying climates. This study explores the historical significance of verandahs, focusing on their evolution, typologies, and functional roles while emphasizing their adaptability in hot and arid regions. This study specifically investigates the intricate relationship between verandahs in traditional houses of the hot and arid region of Kutch and the lifestyle of its inhabitants. The primary objective is to analyze the verandah's role within dwelling spaces and how it responds to contextual and climatic factors, shaping human behavior and social interaction. In the hot-dry climate of Kutch, verandahs play a crucial role in mitigating extreme temperatures through strategic architectural features such as wide overhangs, low-sloping roofs, and enhanced ventilation. The study systematically explores these elements, revealing the symbiotic relationship between verandahs and residents' lifestyles. The findings underscore the verandah's ability to promote thermal comfort, airflow, and environmental cohesion while simultaneously serving as a social and cultural space. By emphasizing how these spaces, rooted in traditional dwelling design, address both climatic challenges and social dynamics, the research contributes to a deeper understanding of the built environment in hot and arid regions, highlighting the continued relevance of verandahs in contemporary residential architecture.

Keywords: Climate-responsive Architecture, Social Cohesion, Traditional Houses, Hot and Arid Regions, Human Behavior, Contextual Parameters, Culture.

INTRODUCTION

The architectural fabric of a place evolves through a complex interplay of multiple layers, encompassing various physical and cultural dimensions. It unfolds as a reflection of the dynamic relationship between the living and cultural patterns of societies, social structures, historical connections, climatic conditions, available material and resources, economic dynamics, and technological advancements, as well as the aspirations of the people. Each layer within this intricate tapestry contributes distinctively, culminating in a complex yet harmonious whole.

Traditional house forms, evolving over extended periods, undergo numerous refining stages. Despite external influences, a continuity of tradition persists, assimilating changes while preserving fragments of its past, upholding intrinsic value. This refinement process, primarily driven by the people inhabiting these spaces, results in a near-completeness of architectural character. Traditional houses are indigenously developed, utilizing local resources and skills effectively. The relationship between inhabitants and these spaces forms a symbiotic bond, guided by traditional principles and spontaneous responses.

In the context of the Indian climate, verandah spaces have played a pivotal role in shaping the lifestyle of its inhabitants.

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They maximize daylight use and provide climatic comfort, especially in the absence of mechanical ventilation. In the traditional framework, the use of verandas, unlike in some societal contexts, has never posed social problems related to privacy. The veranda, therefore, gains significance not only for climatic and social reasons but also in terms of its role in the constructional fabric of traditional dwellings.

The veranda acts as a transitional space, acting as a mediator that seamlessly connects interior spaces, characterized by controlled light and climate, with the natural environment, marked by the unpredictable elements of climate, such as sun, wind, and rain. This research endeavors to delve into the nuanced layers of traditional architecture, particularly focusing on the role of verandas, to unravel the profound connections between built environments and the societies they inhabit.

The exploration of the term "veranda" unfolds a rich tapestry of linguistic heritage and functional diversity, bridging cultural practices with architectural innovation. Originating from an intricate interplay of languages, including Hindi and Bengali, the term finds its etymological roots intertwined with the Portuguese and Spanish word "veranda," connoting a railing, balustrade, or balcony. Defined with precision as an open portico or a light-roofed gallery that graces the front and occasionally other facets of a dwelling, the veranda embodies a multifaceted architectural element designed for protection and interaction with the elements, notably the sun and rain. This nomenclature, particularly in regions such as New Zealand and Australia, extends to denote a structure that not only provides shelter but also interfaces with public spaces outside business premises (Murray & James, Ed. 1989).

A nuanced description elevates the veranda beyond its architectural confines, presenting it as an open, yet occasionally screened area, supported by pillars and often encircled by a balustrade. The veranda's adaptability enables interaction with both the vibrant activity of street life and the peaceful privacy of the home. In the specific climatic and cultural context of Kutch, the veranda is reimagined as a semi-open space, strategically positioned to mediate environmental conditions and social interactions.

The architectural rationale behind the veranda's prevalence in the hot-dry climatic zone of Kutch verandahs emphasizes its role in mitigating heat ingress through strategic material choices, ventilation mechanisms, and spatial planning. The verandah, an essential feature of traditional houses in Kutch, provides not only climatic comfort but also serves as a socio-cultural space. While this study focuses on verandahs in the hot and arid Kutch region, it is essential to note that verandahs or similar architectural elements have been employed in other hot-dry climates around the world. In traditional Islamic architecture, the iwan serves as an integrated shading system that protects walls and openings while enhancing indoor comfort. This semi-open space promotes airflow and reduces heat in hot, dry climates, effectively connecting various areas of the home (Eskandari, Saedvandi, & Mahdavinejad, 2017). Its diverse forms and placements reflect its adaptability, akin to the verandah in Kutch, which also provides shade and ventilation for much of the year.

The concept of the courtyard, prevalent in North African and Middle Eastern homes, serves a similar role, offering shaded areas for cooling and social gatherings (Oliver, 1997). As noted in the study of Islamic house design in Saudi Arabia and Pakistan, courtyards are strategically designed to optimize airflow and maintain privacy, aligning with Islamic values of modesty and spatial segregation (Malik & Mujahid, 2016). The inward-oriented layout of these spaces not only enhances privacy but also fosters microclimates, helping to lessen the effects of the harsh desert climate.

Furthermore, in Iran, the iwan and sardab—a cooling underground space—are integrated into homes to combat the hot climate, showing parallels to the Kutch verandah's climatic role (Mirmoghtadaee, 2009). These cross-regional examples demonstrate a convergent evolution in architectural responses to environmental pressures, as cultures from different regions have developed comparable strategies to create comfortable living environments in hot-dry climates.

This study posits that successful housing must address socio-cultural, economic, and environmental sustainability. The veranda is evaluated in a framework that includes site-specific conditions such as topography and microclimate, along with cultural and symbolic values.

Recognized as a transitional space, the veranda operates at the nexus of the interior and exterior realms, embodying characteristics that are simultaneously semi-outdoor, semi-open, and semi-closed. Its architectural integration as an attached or supplementary element of the main building underscores its pivotal role in facilitating a nuanced interaction between dwellings and their immediate environment, eschewing the inclusion of palaces, institutions, and commercial structures to maintain a focused analytical lens.

This study aims to explore the role of verandahs in the traditional built environment of Kutch. Specifically, it seeks to understand how these spaces are shaped by local climatic and cultural factors, and how they contribute to both environmental comfort and social cohesion. By focusing on verandahs as integral components of residential houses, the study examines their function in balancing climatic challenges and facilitating community interactions.

BACKGROUND

Kutch, an ancient land with a distinctive turtle-like shape, is a peninsula situated between Sindh and Saurashtra in the northwestern part of the state. It is bordered by Pakistan to the north and northwest, Rajasthan to the northeast, Banas Kantha and Patan districts to the east, Surendranagar district to the southeast, the Gulf of Kutch and Rajkot district to the south, and the Arabian Sea to the southwest. Being the largest district in Gujarat, it boasts a coastline of about 406 km. and covers 45,674 sq. km., representing 23.27% of the state's total geographical area. With 51% of the area as a high saline unproductive desert and 34.73% under agriculture, Kutch is characterized by treeless and barren Rann, rocky hills, and low-lying plains.

The Kutch Peninsula is segmented into nine sub-micro regions, each distinguished by topography, climate, geology, soils, and natural vegetation.

Climate of Kutch

The climatic profile of Kutch unfolds with distinctive seasonal variations, characterized by arid and hot summers, cold winters (except in coastal areas), and a notable monsoon season accompanied by strong-willed winds. The annual cycle is categorically divided into four seasons: a frigid interval from December to February, a sweltering phase spanning March to May, a southwest monsoon season extending from June to September, and a post-monsoon period unfolding in October and November.

Throughout the summer and southwest monsoon seasons, the region encounters gentle to moderate winds, intensifying notably in coastal zones, particularly during the monsoons. The period from June to October witnesses prevailing westerly to southwesterly winds, rarely giving way to calm weather conditions. Wind patterns undergo a shift from west to northeast in October, north to east in November and December, and west to northeast in January and February. Between April and September, prevailing winds predominantly originate from the west or south-west. The subsequent months observe a fluctuation between southwest and northwest winds, occasionally veering north or northeast, especially in the afternoons. The colder months are characterized by rigorous east and north winds succeeded by robust south-westerly gales. Dust-laden air is a common occurrence, with April and May ushering in scorching winds and dust storms. October and part of November are distinguished by oppressive and muggy weather. Thunderstorms are prevalent during the monsoon, and sporadic dust storms manifest in summer, particularly within the district's interior.

Positioned beyond the reach of the southwest monsoon along the Tropic of Cancer, Kutch undergoes a sub-tropical monsoon climate within the arid and semi-arid expanse. The annual precipitation from June to September fluctuates between 250-350 mm, with July registering the highest rainfall, encapsulating the climatic intricacies of this region.

Kutchi People, Their Culture and Traditional Kutchi Houses

Kutch has undergone a remarkable economic transformation over the past 23 years, becoming an industrial and tourism hub despite various challenges. This transformation is facilitated by strategic ports like Kandla and Mundra, connecting the region to global trade routes. Also, limited resources prompted some Kutchis to seek opportunities abroad, leading to a diverse diaspora engaged in various businesses.

Kutch is a melting pot of communities, with people speaking languages like Kutchi, Sindhi, Gujarati, and Hindi. The predominantly Hindu and Jain population follows a vegetarian lifestyle. Kutchi costumes, known for their uniqueness, feature intricate embroidery and mirror work and reflect the rich tapestry of different communities, which are identifiable by distinct handicraft patterns and dress styles. The area's unique geography has cultivated a rich culture known for diverse arts and crafts.

The architectural landscape in Kutch exhibits a nuanced variability contingent upon the diverse climatic regions

within the district. This variation is particularly pronounced in the hot-humid and desert regions, each influencing the design and construction of traditional dwellings.

Kutch's socio-cultural fabric is deeply rooted in a respect for native culture and caste. While the joint family system persists, it undergoes gradual disintegration due to occupational diversification. Women play a pivotal role in household management, and their substantial engagement in economic activities, agriculture, labor, and handicrafts, especially in rural areas, contributes significantly to the social dynamics of the region.

The climatic regions of Kutch have a profound influence on the development of traditional dwellings. In the hot-humid region, characterized by high humidity, dwellings incorporate large verandas and semi-open spaces to harness winds while minimizing solar heat gain. The hot-dry region emphasizes smaller openings, with extensive use of large verandas and overhangs to combat solar heat and hot winds. In the extreme hot and cold climate, minimal openings prevail, with verandas strategically constructed to enjoy moderate climates during specific times. Diverse building materials, including stone, wood, grass, and clay, contribute to the distinctive forms of houses across Kutch.

The architectural approach to house design in Kutch seeks a harmonious integration of various elements to achieve an optimal balance between the desire for the evening sea breeze, daytime heat protection, and a seamless connection with the outdoors. The design aims to shield occupants from the hot breeze and solar radiation while facilitating the influx of cool breezes. Notably, the veranda stands out as a vital and historically significant climate-friendly space. The veranda dynamically adapts to the climate, allowing controlled exposure to sunlight and facilitating the flow of cool breezes. It seamlessly integrates indoor and outdoor activities, accommodating a variety of uses for both household members and visitors. In essence, the veranda emerges as a flexible and inclusive space, responding to the diverse needs of its occupants within Kutch's unique climatic context. This study aims to delve into the intricate details of these veranda spaces, motivated by the diverse background of Kutch and its rich interplay of history, culture, and architectural innovation.

METHODOLOGY

This research delves into the relationship between traditional verandah spaces and lifestyles through a primary study of selected case studies. The methodology ensures a rigorous exploration of verandas in the hot-dry region of Kutch, examining their contextual, climatic, and social significance.

The first stage includes a careful selection of case studies based on predetermined criteria. In the second stage, detailed data compilation in various formats involves drawings, charts visually representing activity patterns, and summaries from interviews to provide deeper insights. A pivotal aspect of the study involves a nuanced understanding of occupants' activities, emphasizing the seasonal variations that influence engagements. Veranda comparisons contribute to constructive inferences. The third stage examines compiled data, focusing on context, typology, built conditions, climate response, social parameters, and human interactions within the veranda. The systematic evaluation of its spatial dimensions and layout, aims to provide valuable insights into the intricate dynamics inherent in residential environments.

The concluding stage involves a comprehensive comparison of gathered information, emphasizing the identification of constants and variables. Synthesized insights draw upon extensive analysis and inferences made throughout the research study.

DATA COLLECTION AND ANALYSIS

This research focuses on the village of Naredi in the Abdasa Taluka, Kutch district, covering 2,398.26 sq km with 168 villages. Naredi, situated 60 km from Bhuj, has a historical background dating back 400 years, transitioning from a Rajput community to including Jain, Bhanushali, and Muslim residents. The village, housing around 2500 people, maintains ancestral homes and exhibits gradual growth compared to nearby centers. Its selection is deliberate, considering its distance from the 2001 earthquake epicenter, resulting in less damage and offering an opportunity to study older houses. Migration-related vacant homes pose limitations but provide a unique research opportunity.

Image 1: Map of India showing the Gujarat state

Image 2: Showing the Location of the Selected Village of the Kutch

Image 3: Showing Location of Selected Houses in Naredi Village, Abdasa, Kutch

Reference: **Survey of India, Department of Science & Technology**

Reference: **Image 2 & 3: Google Earth**

Table 1: A Comparative Study of Residential Data Collection

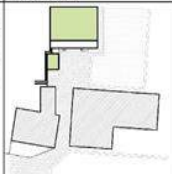
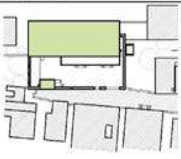
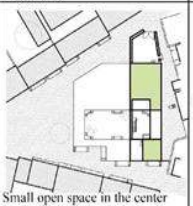
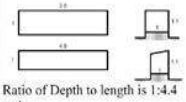
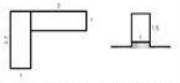
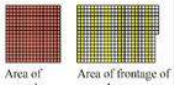
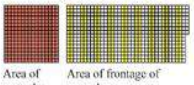
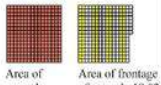
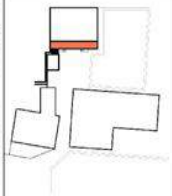
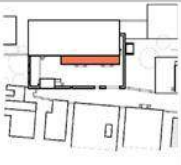
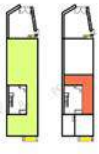
No.	HOUSE / ISSUES	HOUSE 1	HOUSE 2	HOUSE 3	HOUSE 4	HOUSE 5	
1.	What is there in front of verandah.	Large open space in front, having otala and one tree.	Back verandah having more open space and Large otala.	 Veranda facing Small closed chowk and narrow street.	 Paved Open space in front with high wall of vanda.	 Small open space in the center and back of house.	What kind of external things matter in the way verandahs are used.
2.	Scale and Proportion of veranda	Ratio of Depth to length is 1:6.6 and Width to height is 1:1.4	 Ratio of Depth to length is 1:4.4 and Width to height is 1:1.1	Ratio of Depth to length is 1:6.7 and Width to height is 1:1.2	Ratio of Depth to length is 1:7.1 and Width to height is 1:1.5	 Ratio of Depth to length is 1:2.9 and Width to height is 1:1.5	Is there any influence of this ration on the way verandah is being used.
4.	Degree of openness of verandah. • Area of veranda in smt • Area of frontage of veranda smt	 Area of veranda: 57.36 Area of frontage of veranda: 84.27	 Area of veranda: 12.76 Area of frontage of veranda: 28.05	 Area of veranda: 18.74 Area of frontage of veranda:18.02	Area of veranda: 26.89 Area of frontage of veranda: 32.05	Area of veranda: 34.87 Area of frontage of veranda: 33.07	What is the effect of such openness on the way spaces around such elements of verandah.
3.	Elements in verandah	1. Stapes 2. Plinth 3. Lean roof 4. Wooden Column & Beam 5. Non-loadbearing deco column 6. Door and window 7. Wooden Railing 8. Fascia	1. Stapes 2. Plinth 3. R.C.C Slab 4. R.C.C/Precast Column and Beam 5. Door and window 6. Gokh	1. Stapes 2. Plinth 3. Lean roof 4. Wooden Column and Beam 5. Door and window 6. Gokh	1. Stapes 2. Plinth 3. Lean roof 4. Stone Column and Wooden Beam 5. Door and window 6. Facia 7. Gokh	1. Stapes 2. Plinth 3. R.C.C Slab 4. Wooden ceiling 5. Door and window 6. Zapali 7. Wooden grill 8. Gokh 9. Kyaro	Studying the responses that gets developed around such elements in veranda.
6.	Available terrace / other veranda / otala. Otala Veranda Terrace						Is there any influence of such other open / semi open spaces available on the way main verandah is being used.
7.	Serraouding conditions	House is located on Main Street of the village. On its backside, there is small open ground. All residences around are of the same scale.	House is located on the adage of the village. House has two entrances and both are open up in the small chock. On its backside, there is a seasonal river. All residence around.	House is located on the adage of the village. It has no vanda and its veranda is open up directly to the small chock which leads to the tertiary street of the village. On its backside, there is a seasonal river. On its side there is vacant plot and all residence around.	House is located almost in the middle part of the village. On its side and back, there is a same type and same scale residences. On its front, there are new one-story residences only for the Jain community. We can access through it from the tertiary street of the village.	House is located in the center of the village chock, which divide the single street in to two main village streets.	How such conditions influences the manner in which verandah is used.

Table 2: A Comparative Study of Residential Data Collection

No.	House Built in	House 1	House 2	House 3	House 4	House 5
1	No. of Family	1907	1945	1975	1935	1925
2	No. of Family Members	12	6	5	6 Members	5
3	Occupation	Electrician	Farming, Village Sarpanch	Job in GIDC	Farming	Farming
4	Veranda type	Linear	Linear	Linear	Linear	L Shape
5	Total plot area in smt.	917.38	653.3	115.66	346.11	463.1
6	Area of vanda in smt.	917.38	653.3	–	346.11	208
7	Frontage of verandah in smt.	265.73	51.34	–	101.62	27.8
8	Area of backyard in smt.	–	289.1	–	–	38.74
9	Living area in smt.	17.94	11.98	12.63	52.19	32.96
10	Sleeping area in smt.	49.19	30.89	16.91	14.84	23.15
11	Cooking area in smt.	16.77	5.16	7.79	6.55	3.3
12	Verandah area in smt.	57.36	12.76	18.74	26.89	34.87
13	Total built up area in smt.	424.58	221.5	113.08	225.9	129.1
14	% of Built up to plot area	46.28 %	33.90 %	97.77 %	65.27%	27.88%
15	Built-up area available per person	35.38 %	36.92 %	22.62 %	37.65%	25.82%
16	Veranda area available per person	4.78	2.13	3.75	4.48	6.97
17	Percentage of verandah	13.5 %	5.76%	16.57 %	11.90%	27.01 %
18	No. of doors in veranda	3	5	2	2	4
19	No. of windows in veranda	2	7	4	6	8
20	Number of Rooms in House	3	2	2	2	2
21	Type of structure	Load bearing				
22	Avg. structural span in meter.	3.5 m	3.8 m	1.3 m	2 m	2.1 m
23	Main structural material	Wood, Stone				
24	Number of houses in chock/ street	5 Houses	3 Houses	1 Houses	5 Houses	More than 10 Houses

Reference: **Table 1 & 2: (*Source* : Author)**

RESULTS AND DISCUSSION

In the framework of this research paper, the discussion is systematically categorized to delve into specific aspects of the veranda. These categories include Veranda and Typology, Context, Built Conditions, Construction, Climate, Social Parameters, Human Interaction, and Human Psychology. The human interaction and psychological parameters are analyzed through the mapping of the activities of the individual, observations, as well as interactions. This systematic categorization allows for a comprehensive exploration of the multifaceted roles played by verandas in the lives of individuals and communities.

The veranda serves as a semi-open space intricately linked to indoor areas and exhibits distinct characteristics such as low height for solar radiation protection, a strong link with the front street or Chowk, a higher plinth defining its territory, and accommodation of facilities for various activities. The key is its open frontage, sometimes partially covered, enhancing control and maintaining a connection with the surroundings. The presence of posts/columns not only serves structural purposes but also reinforces the sense of territorial boundaries. Important assets like Paniaaru, rasoi, charpai, and hichako contribute to the functionality of the veranda.

During visits to Kutch, observed verandas not only displayed vibrancy and liveliness but also held significance in terms of social connectivity, privacy without complete isolation, low-profile dominance, family spaces with community relevance, and the seamless integration of tradition with contemporary needs. These verandas, acting as dynamic spaces, effectively accommodate both familial and occupational requirements. In this well-defined architectural space, by analyzing the behaviors of individuals within these varied criteria, we can gain valuable insights into the dynamic nature of verandas and their significance in the broader socio-cultural context.

Veranda and Typology

In the hot and arid region of Kutch, verandahs play a critical role in mitigating climatic extremes while simultaneously functioning as spaces of social interaction, shaped by the cultural practices of the region. The verandah, a pivotal architectural feature in Kutch, has evolved as a significant element of traditional houses. Three main shapes characterize the typology of verandahs in this area: Linear, L Shape, and C Shape Verandah. The Linear verandah, oriented towards the street or front open space ('vando'), establishes a strong connection with the front, while sporadically, houses incorporate verandahs in the expansive rear open spaces. The L-shaped verandah strategically manages connections with outdoor spaces, whereas the C-shaped verandah, though rare in Kutch houses, distinctly isolates outdoor areas.

The positioning of verandahs in specific architectural patterns—linear, L-shaped, and C-shaped—produces different functions and perceptions within the home. Linear verandahs, often opening directly to the street, offer a strong visual connection to the public realm and are typically used for welcoming visitors, casual conversations, or monitoring street activities. However, this positioning may limit privacy, especially in homes where multiple households share communal spaces. The L-shaped verandah, by contrast, carves out a more personal territory. Its configuration allows for discrete activities, creating more intimate, sheltered spaces that offer a higher degree of privacy for family members. C-shaped verandahs, although less common, are introverted by design, enclosing a central space that enhances privacy and control over activities within the household.

The typology of verandahs not only determines their spatial arrangement but also influences the social interactions and daily routines of the inhabitants. In Kutch, where homes serve as both private and communal spaces, the layout of the verandah plays a critical role in defining the balance between public engagement and familial privacy.

This architectural vocabulary emphasizes that verandah placement plays a critical role in determining how spaces are perceived and utilized, whether for social interaction, private family time, or functional tasks.

People, Veranda and Typology

Having explored the basic typology of verandahs, it is essential to understand how these variations influence the daily lives and behaviors of the inhabitants in the context of Kutch's traditional architectural practices. Within these verandah categories, variations emerge, influencing the opportunities they afford to individuals. Linear verandahs, when linked to a linear house form, may impose limitations, guiding human responses based on edge conditions and expectations. The close connection with the street makes linear verandahs more accessible to public interaction, but also limits privacy, especially for houses where the verandah is directly exposed to communal spaces.

L-shaped verandahs carve out a well-defined personal territory, fostering opportunities for discreet activities and introducing greater tonal variations to satisfy diverse needs. These verandahs are more flexible, providing semi-private areas where family members can engage in intimate conversations or household chores without being in full view of passersby. Although not extensively covered in case studies, general observations imply that C-shaped verandahs exercise heightened control over central open spaces, resulting in a more introverted typology characterized by enhanced privacy.

In structures with ground + one story, a common configuration involves verandahs on the ground floor and terraces or balconies on the first floor. Verandahs are vibrant spaces during the day, often transforming into

sleeping quarters on hot summer nights. In contrast, upper semi-open spaces see reduced activity during the day. Surprisingly, the presence of trees has a limited impact on verandah usage, unlike their more pronounced influence on open spaces. This exploration scrutinizes the intricate relationship between verandah design, typology, and human behavior in the dynamic context of the Kutch region.

In Kutch, verandahs are prominently oriented towards the front of the house, directing their facades either to the street or the front open space, locally known as 'vando.' The frontage of the house emerges as a substantial contextual force, intricately shaping the verandah and dictating activities in its proximate vicinity.

Contextual Determinants of Verandahs in Kutch

The contextual determinants of verandahs are multi-layered, encompassing several key factors:

- **Shared Spaces:** Adjacent linear verandahs contribute to the creation of shared spaces.
- **Extension through Vegetation:** The presence of trees and otala (raised platforms) in the frontal area extends the influence of the verandah.
- **Utilization of Front Space:** The utilization of the front space sets the overarching context for verandah activities.

Image 4: A linear veranda spans across adjacent houses along a village street.

Image 5: The adjacent tree and otlo function as an extension of the veranda.

Image 6: Birds are on the otla located in front of the veranda.

Image 7: Cows are in front of the veranda

Images 4,5,6 & 7
(*Source:* Author)

Image 8: The formal entrance to the veranda, a paved path, small plants surrounding the periphery, and a lawn collectively contribute to creating a pleasant ambiance.

Image 9: The veranda is well-suited for easy accommodation of household members, children and visitors.

Image 8 & 9
(*Source:* Author)

- Verandahs, meticulously designed in response to their immediate surroundings, are shaped by the conditions at the front of the house. The size of the front space plays a pivotal role in influencing the intricacy of the verandah, where open areas serve as versatile, multipurpose family spaces. Notably, verandahs situated along busy streets may have elevated plinths to accommodate specific activities tailored to their dynamic surroundings. This research explores the interplay of environmental and spatial factors in shaping verandahs in the Kutch region, with similar parallels drawn from other hot-dry climates.

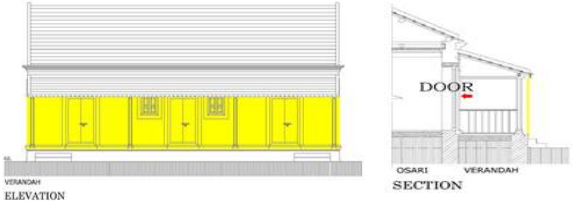
People, Veranda, and Context

Understanding the multifaceted roles that verandahs play within the architectural and social fabric of communities, it becomes essential to transcend mere architectural analysis and delve into the realm of sociocultural dynamics that shape their utilization. These contextual determinants create a foundation upon which individual and communal interactions with verandahs evolve, influenced by cultural and environmental factors. This broader exploration reveals how local traditions, cultural norms, and social structures intricately influence the patterns of verandah usage, rendering these spaces as narratives of the communities' living culture.

In Kutch, the immediate physical environment—including elements like local vegetation, elevated plinths, and designated cattle areas—significantly dictates the functional dynamics of spaces adjacent to verandahs. Such environmental factors not only delineate spatial usage but also shape the social interactions that unfold within these thresholds, thus defining the verandah's role in enhancing human connectivity and communal cohesion (Zuhairuse Md. Darus *et al.*, n.d., as cited in Darus *et al.*, 1999). Additionally, the interplay between physical conditions and human behavior underscores the complexity of interactions enabled by verandahs, highlighting their capacity to influence and be influenced by the local context (Bay & Ong, 2006, as cited in Darus *et al.*, 1999). Similar to the Malay traditional houses, where verandahs serve as transitional spaces adapting to both social and environmental needs, the Kutch verandah serves as an interface between indoor and outdoor spaces, reinforcing communal and family bonds through its architectural layout (Philip Gibbs, 1987, as cited in Darus *et al.*, 1999).

Direct physical linkages, such as street-facing verandahs and proximity to natural features like shade trees, further impact the activities conducted on these verandahs. Such features extend the spatial and perceptual boundaries of the verandah, inviting a diversification of activities that blur the lines between public and private domains, a distinctive feature of Kutch's communal life (Ozaki, 2001, as cited in Darus *et al.*, 1999). In both Malay and Kutch contexts, verandahs oriented towards the front street not only enable engagement with community activities but also maintain a sense of privacy for household members, facilitating a strategic spatial arrangement that enhances daily life interactions (Philip Gibbs, 1987, as cited in Darus *et al.,* 1999). In essence, verandahs in Kutch serve as dynamic architectural elements that respond to and shape their contextual environment. They are sites of complex interactions, where architectural design, environmental factors, and sociocultural dynamics converge, catalyzing a spectrum of activities that enrich the local residential experience. Elevated verandahs on busy streets, much like those in Malay traditional housing, demonstrate an adaptation to social and environmental demands, creating spaces that reflect and reinforce cultural values within the Kutch community. Through this lens, verandahs emerge not merely as physical structures but as vibrant arenas of social engagement and cultural expression, mirroring the nuanced lifestyles of Kutch inhabitants. These verandahs stand as cultural and social markers, dynamically shaping and reflecting the values, behaviors, and identities of the communities they serve (Bay & Ong, 2006, as cited in Darus *et al.*, 1999).

VERANDA AND BUILT CONDITIONS



Drawing 1: The drawing shows the vertical plane demarcated by the veranda's front edge. Also, it highlights the veranda's role in creating the perception of a formal entrance to the osari.

(*Source:* Author)

The verandah's significance within the architectural arrangement is shaped by material composition, orientation, construction techniques, and connections with front and back elements. The integration of local materials and traditional construction techniques highlights the verandah's meaningful role in the broader context of traditional dwelling spaces.

In the creation of verandahs, various elements play distinct roles in shaping built conditions. It is crucial to understand these elements and their inherent characteristics:

- **Roof Structure:** Verandahs typically exhibit a lean-to roof with a front slope, fostering an introverted ambiance. The spatial arrangement between columns simultaneously invites connection and introspection. This roof can either be an extension of the house's roof or an attached lean-to structure.
- **Parapet Walls:** Verandahs may feature small parapet walls in front, serving as an additional layer of protection and functioning as versatile elements that can be utilized in various ways.
- **L-shaped Houses:** L-shaped houses provide a higher degree of privacy in the front verandah, fostering freedom in accommodating personal family activities. In such cases, even cooking and dining may frequently take place in the verandah.
- **C-shaped Verandahs:** C-shaped verandahs can be likened to semi-courtyard houses, where the central open space becomes a vibrant family hub. This space extends as an extension of every room.
- **Functional Areas:** Verandahs often house primary activity spaces, such as cooking areas and water-related wet zones. The configuration of these spaces varies based on the verandah's shape, whether L-shaped, C-shaped, or linear.
- **Furniture Placement:** The arrangement of furniture in the verandah is primarily dictated by the general circulation pattern and lighting conditions within the space.
- **Grills and Privacy**: Verandahs adorned with grills convey a heightened sense of privacy and confidentiality, offering protection from dust and heat. However, this comes at the cost of reduced openness, connectivity with the outside, and diminished wind flow. Grilled verandahs are often favored in houses with frequent closures.
- **Proportional Area:** The area of the verandah typically ranges from 16% to 26% of the total house area. In smaller houses, the verandah area tends to be more substantial, serving as an effective multipurpose space. Larger houses, on the other hand, witness compartmentalization of activities, with verandahs retaining a traditional and connecting role.
- **Verandah Facing Open Space:** Verandahs with larger dimensions facing open spaces act as meeting points between indoor and outdoor realms, alternating between being a room and an open area. In essence, the functionality and definition of verandahs are significantly influenced by the quality and nature of the built house.

Image 10: Verandas with small parapet walls in front

Image 11: A veranda featuring a grill.

Image 12: The small linear veranda visually extends the house's roof. Within the veranda, the rasoi is positioned at its edge, extending onto the otla.

Images 10,11 & 12
(*Source:* Author)

- **Evolution of Verandahs Over Time:** Over the generations, the role of verandahs in Kutch has evolved significantly. Traditionally, verandahs were essential for climatic adaptation, serving as spaces for family interaction, work, and leisure. However, with the advent of modern technology, including mechanical cooling and shifts in family dynamics, the function and perception of verandahs have changed. In contemporary Kutch, particularly in urban areas, verandahs are often designed to be smaller and more decorative, emphasizing visual appeal rather than serving the diverse functional purposes they once held.

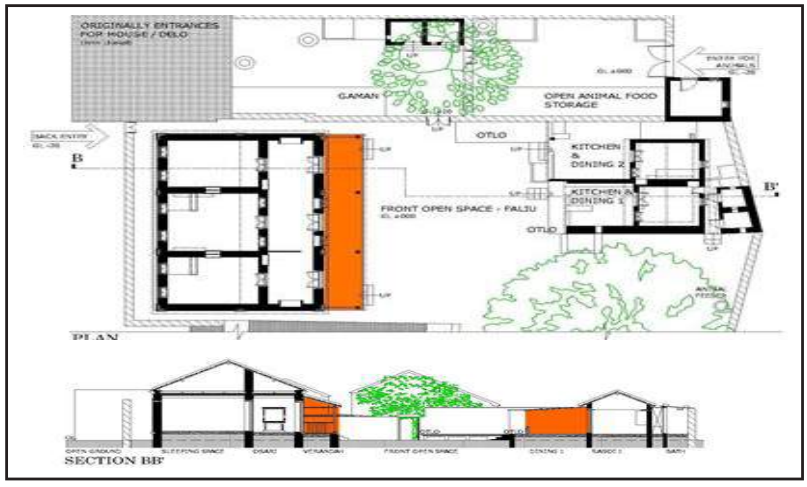
As families transition from joint to nuclear structures, the verandah's role as a transitional or social space has diminished in urban areas. Verandahs in cities tend to reflect a shift towards indoor living, with their functional roles increasingly relegated to aesthetics. However, in rural areas, the verandah remains a vital part of daily life, preserving its traditional multi-functionality as a space for work, family gatherings, and rest. The evolution of verandah use over time reflects broader socio-economic and cultural changes, signaling a shift in how architectural spaces are used to meet modern needs. Despite these changes, verandahs continue to be integral to the environmental and social life of Kutch, maintaining their importance in adapting to the region's climate and lifestyle.

People, Veranda, and Built Conditions

The constructed verandah holds immense potential for diverse uses, but these applications are inevitably influenced by the available fixtures and facilities. The form and size of the verandah direct attention to the front through a vertical plane, often defined by its front edge. This plane may find support from single or multiple columns, with parapet walls reinforcing its verticality. While such walls facilitate visual communication, they simultaneously limit direct physical connections with the external space. The extroverted quality of verandahs, characterized by their reach out to the public, renders them extensively used.

Verandah doors act as formal entrances, marking private areas, and changes in roof profiles further distinguish the nature of privacy. The scale of the verandah is carefully calibrated to ensure comfort, making it the most amiable space within the dwelling. By its nature, the verandah becomes a friendly and inviting space, offering an appropriate scale, simple articulation, good orientation, necessary connectivity, engaging accessories, climate-friendly conditions, social relevance, a traditional perspective, and ample potential for activities.

Specifically, elders gravitate towards sitting near freestanding columns or in cornered spaces, emphasizing a sense of proximity. Housewives seek locations that afford visibility while maintaining a degree of seclusion, controlling the entire space when engaged in household activities. Men, utilizing the verandah during early and late hours, prefer spaces that provide a sense of personal territory. Children claim the entire verandah as their domain, utilizing every corner for play, meals, sleep, and study. The verandah's familiar nature, grounded in traditional materials and details, makes it an easily accepted and predetermined space. The integration of various structural and decorative elements enhances the verandah's functionality and visual appeal, contributing to its meaningful role in the overall dwelling experience.



Drawing 2: Plan and Section show the Relation of the veranda with indoor and outdoor spaces. (*Source:* Author)

Image 13, 14, 15 & 16: In this veranda, the fundamental need is to establish individual territories while fostering interaction. In the first house, a charpai serves as a temporary element to delineate personal space. In the second house, a permanent element is introduced in the form of a wall with a substantial puncture, not only defining space but also providing a seating element for interpersonal interactions. The 15th &16th image shows the differentiation of activities within the veranda through changes in flooring conditions.

Image 17: Strategically placed plants significantly modify the verandah space, introducing additional layers to create a welcoming environment.

Images 13,14,15,16 &17 *(Source:* Author)

Veranda and Construction

The dimensions of dwelling spaces, beyond the constraints of available land, are significantly governed by materials and technology. While traditional houses predominantly utilized materials such as mud, brick, stone, wood, and clay tiles, with bricks, and stone forming vertical load-bearing elements, and wood used in roof structures. These materials played a vital role in shaping the thermal dynamics of the dwelling. Thick mud and brick/stone walls prevented thermal conductivity, ensuring a comfortable internal climate. Wood's heat-resistant properties enhanced overall thermal performance and clay tiles allowed the escape of hot air, providing a distinctive breathing quality. The use of local materials like mud lipan and natural stone flooring contributed to climatic comfort in both the veranda and the entire house.

In essence, the veranda's significance within the architectural arrangement is shaped by material composition, orientation, construction techniques, and connections with front and back elements. The integration of local materials and techniques from traditional house construction highlights the veranda's meaningful role in the broader context of traditional dwelling spaces.

Image 18: Contemporary materials are utilized to create a veranda of a similar style.

Image 19: In the creation of a veranda for a double-height house, traditional aesthetics were achieved with stone as the primary building material.

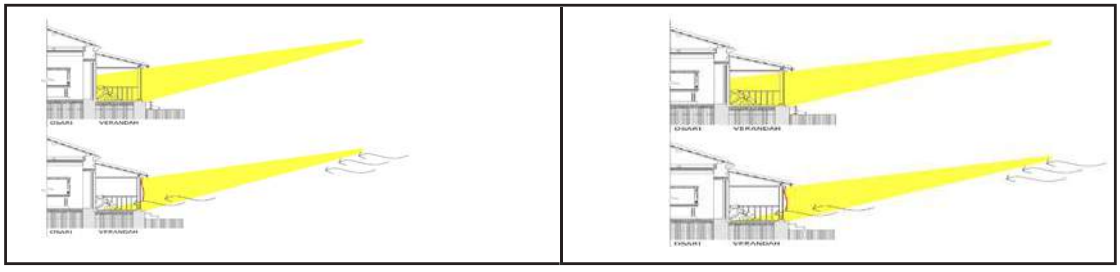
Images 18 & 19 *(Source:* Author)

Veranda and Climate

The climatic attributes of the veranda play a significant role in enhancing its comfort. Its nearly blocked side prevents cross-ventilation of hot air, and two perpendicular sides impede heat entry. A low roof profile minimizes direct solar heat gain, transforming the veranda into a pleasant space for year-round use when strategically oriented. In the selected region, addressing direct solar heat gain and hot air flow is crucial due to high temperatures and dryness. Traditional wisdom in this region addresses climatic challenges through methods like thick mud brick walls to enhance thermal

resistance, lower-leaning roof profiles and larger overhangs for shading, Preventing cross-hot air circulation through small or closed windows, leveraging sea breezes, utilizing outdoor conditions during the monsoon, and strategic orientation with vegetation as a modifier when applicable.

The region of Kutch experiences a daily cycle of wind direction, with cool and pleasant breezes during the day flowing from the sea and reversing at night. The low roof height reduces solar heat gain to some extent (extreme hot conditions still pose challenges), and the high plinth keeps dust away. Hangings, movable partitions, and water sprinkling provide temporary protection from seasonal forces. During winter, winds shift direction, and in the monsoon, occasional rain is welcomed. As outdoor temperatures fall in the evening, the veranda becomes comfortable and socially active. It consistently maintains its use in different seasons, with only the timings of activities shifting. Activities find an appropriate space in the veranda, adapting to the varying seasons.



Drawing 3: The drawing depicts a veranda with a low roof height, designed as a wind-catching device. It also shows the veranda level and temporary sun protection achieved through hangings.

(*Source:* Author)

Veranda and Social Dynamics

The verandah, with its distinct character, persists as a continuous and well-established trend in building typology, transcending professions and cultural backgrounds. It fosters a sense of belonging, transcending caste and community, and serves as a defining feature of both the dwelling and the family. A glance at the verandah often reveals the social and economic status of a family, positioning it as the most "public" space within the dwelling, accommodating everyone without discrimination, yet maintaining a degree of confidentiality through high plinths or the use of grills.

Socio-Economic Variations in Verandah Usage

Verandahs in Kutch are not uniformly utilized across socio-economic classes. Wealthier merchant families, for instance, tend to use verandahs as leisure spaces, often elaborately decorated to reflect status. These verandahs are typically larger, intended to accommodate social gatherings, and act as a display of the family's wealth and social standing. In contrast, in lower-income or agricultural households, verandahs serve multifunctional purposes, such as spaces for household chores like weaving or food preparation. The size, orientation, and function of the verandah reflect the socio-economic standing of the family. In traditional farming households, the verandah may serve as a storage area for tools, food grains, or even cattle. The use of verandahs as markers of socio-economic identity becomes clear when examining the types of activities and the degree of formality associated with the space, varying from highly communal spaces to personal or work-related areas.

By comparing verandah usage across different socio-economic strata, this research highlights their role not only in climatic adaptation but also as socio-cultural symbols reflecting a family's status within Kutch society. In addition to these socio-economic variations, the verandah's role extends beyond its economic symbolism, functioning as a critical social space for families across various strata.

The size and decoration of the house communicate status within the social hierarchy, reflecting a family's aspirations and choices. The verandah acts as a buffer space, preserving sanctity, privacy, and confidentiality for the indoor areas. Building finishes and furniture richness convey occupants' impressions, while verandah size mirrors lifestyle and occupation. Houses without verandahs signify a sense of 'isolation' from the broader societal context.

Image 20: Traditional rituals are conducted near the verandah, and spectators occupy the verandah space to witness and partake in the enjoyment of these rituals.

Image 21: During the evening hours in the veranda, children engage in observation and playful interactions with friends. Simultaneously, mothers are involved in Embroidery, with daughters actively attempting to acquire and master this skill.

Images 20 & 21 ***(Source:*** Author)

In the broader context of the house, the veranda emerges as the most socially activated space, facilitating interactions within the family and with visitors. Here Are observations in this region tell its key roles:

Family Hub: The veranda serves as the space where most family conversations unfold, setting the tone for the family's nature and concerns.

Multifunctional Space: It acts as a passage and a participatory space, creating a sense of family, belongingness, and authority. Children engage in homework and play, women balance household work and conversations, elders oversee and participate, and men relax while cherishing family bonds.

Social Nexus: The veranda establishes both casual and formal social linkages, accommodating activities ranging from tea gatherings to marriage discussions. It serves as a stage for negotiations and conflict resolution, religious rituals, social functions, and even household industries like papad-making or agricultural product storage.

Public Image: Society perceives families through their verandas, making it a check for the image projected by each family. The veranda establishes a strong connection with and exposes the family to society, embodying mutual connection and control.

Cultural Mirror: Families project themselves through their houses, and in traditional houses, the veranda becomes a reflection of the house. Just glimpses of the veranda can provide insights into a family's social and cultural status.

Versatile Space: The inherent nature of the veranda grants freedom for diverse uses, making it a space with maximum potential for interventions and interactions. Philosophically, the veranda represents a phenomenon that offers considerable liberty in personal, social, and cultural dimensions.

Any space that is climatically comfortable and contextually appropriate inherently accommodates a range of human activities across different layers.

Veranda as a Social Institute within the Dwelling

The veranda can be considered a social institute; it is primarily an integral part of the house. As the face of the house, the veranda plays a crucial role in meeting social requirements more profoundly with warmth and depth.

Women's Social Haven: Neighboring women gather in the veranda, engaging in various feminine activities during afternoons, transforming it into a genuine social institute for women.

Children's Playground: Children and their friends converge in and around the veranda, maintaining constant visual contact with elders who guide, control, and monitor them. The veranda becomes a nurturing space for various activities.

Elders' Wisdom Corner: For elders, the veranda is a place to impart life lessons, teach skills, values, and engage in activities based on their health.

Men's Retreat: For working men, the veranda serves as a leisure space and a private retreat. Depending on personal preferences, it can also function as a dynamic community space, though this may require balance to avoid disrupting other family activities.

In essence, the veranda goes beyond being a physical structure; it is the beating heart of the home, fostering connections, nurturing traditions, and reflecting the diverse tapestry of family life.

Veranda and Human Interactions

The veranda, primarily oriented towards the front, serves as a crucial space for diverse human activities, influenced by visual connectivity, climatic comfort, and perceived authority. Usage within a family is strategically determined by daily roles played by individuals, and the location of amenities shapes veranda utilization. Elders prefer supportive areas with facilitating furniture, adults align spaces with their purpose, and children, being adaptable, find spaces wherever available. Veranda activity peaks in the mornings and early evenings, reflecting human responses influenced by local climate patterns.

Similar to the hierarchy observed in houses, verandas exhibit a spectrum of spaces ranging from interactive to silent, climate-friendly to discomforting, and accommodative to less accommodative. Users recognize these qualities and adapt their activities accordingly. Once established, veranda spaces are generally accepted, and users adjust to existing conditions, fostering a lively atmosphere.

Verandas, due to their inherent nature, become versatile spaces accommodating short-term storage for both occupational and household needs. Despite the presence of storage, veranda patterns remain relatively stable, displaying the adaptability of the space. The veranda's unique characteristics, offering minimal permanent facilities but maximum flexibility for bringing in additional furniture, contribute to its dynamic use.

Individuals seek varied conditions for activities, making verandas adaptable for diverse uses, from study desks to collective dining setups and makeshift sleeping arrangements for guests. The dynamic and versatile nature of verandas positions them as the most usable spaces within a house, providing opportunities that other areas may not, and family members optimize their usage based on personal expectations and house limitations.

People, Veranda, and Human Interactions

According to Indian Darshan-shastra, human responses are influenced by an individual's nature and preconditioning, external factors, and the connection between the external factors and the individual. Despite diverse social groups in Kutch, the nature and features of verandas remain relatively constant, contributing to consistent behavioral patterns.

Veranda's responses show limited diversity due to the constant climate, culture, resources, values, and the consistent nature of verandas across social groups. Despite varying house typologies, response patterns remain relatively constant. Verandas, beyond their utilitarian function, evoke strong connections due to familiar conditions, serving as the heart of the house and accommodating diverse needs throughout the day.

Image 22: Placing a 'toran' at the entrance within the veranda not only conveys a welcoming atmosphere but also showcases the skill of the women.

Images 22 (***Source:*** Author)

Image 23: To avoid allowing certain community members into the house, exchanges take place in the veranda. In this manner, the veranda serves as an intermediary space, fostering comfort for all involved.

Images 22 & 23 (*Source:* Author)

Women showcase skills through crafts, children use verandas as play and learning areas, and adults engage in sharing, participating, and personal growth. Elders find verandas conducive to staying in touch, guiding

younger members, feeling responsible, and engaging in chosen activities. Positive responses stem from favorable conditions like climate responsiveness, human-scale design, The veranda, with its diverse opportunities, every family member, reflecting its significance beyond functionality.

Veranda and Psychological Dynamics

The verandah plays a pivotal role in establishing profound psychological connections among individuals. Unlike enclosed spaces, it fosters a sense of interconnectedness, granting freedom to engage with external events. This lack of confinement allows for movement and creates an ambiance where individuals, even in inactivity, find their minds captivated by various elements and events surrounding the verandah.

The design promotes social interaction, acting as a catalyst for the close-knit community. The aesthetic elements within the verandah contribute significantly to its welcoming and friendly nature, enhancing the overall psychological impact.

Image 24: Grandmother observed children engaged in play and leisure activities in the open space, while seated in the veranda.

Images 24: (*Source:* Author)

Cultural influences are also integral to understanding the verandah's impact, as cultural elements can shape perceptions and interactions within this space. Examining whether individuals tend to personalize the verandah further enriches the observation, shedding light on the role of personalization in strengthening the psychological connection to the environment.

In summary, the verandah, with its friendly scale and absence of overpowering elements, not only serves as a physical space but also as a facilitator of a harmonious and inclusive psychological environment. Considering social dynamics, aesthetic elements, seasonal variations, cultural influences, and personalization and personalization captures the multifaceted nature of the verandah and its psychological significance comprehensively.

CONCLUSION

This research highlights the pivotal role of verandahs in the traditional architecture of Kutch, emphasizing their importance in addressing both climatic and socio-cultural needs. Verandahs not only enhance the quality of life but also contribute to safety, social interaction, and cultural continuity. The study addresses a research gap by exploring the multifunctional role of verandahs within the built environment. Key findings include:

i. **Climatic Adaptation through Contextual Design:** Verandahs in Kutch are shaped by essential needs and contextual factors. Their design, characterized by elements such as scale, plinth elevation, and a controlled semi-open structure, creates climate-responsive and interactive spaces. These constants challenge the notion of significant variation, as shown in Images 10, 11, and 12.

ii. **Balance between Public and Private Spaces:** Verandahs act as transitional zones, blending public visibility with private domestic functions. As shown in Image 12, they serve as spillover spaces that indicate ownership while restricting specific actions.

iii. **Plot Size and House Orientation:** Traditional house orientation in Kutch is influenced by plot size and resources, rather than solely by climatic conditions. Table 2 challenges the assumption that climate is the primary factor, revealing practical considerations as key determinants.

iv. **Proportionality of Verandah Size to House Area:** The size of the verandah correlates with the overall house size, typically comprising 18% to 26% of the total house area, as seen in Table 1. Smaller houses utilize verandahs more intensively, showcasing their flexibility in resource-constrained households (Images 8, 9, 10, 16, 17, and 21), while larger houses allocate a smaller percentage of space to verandahs, reflecting a preference for larger indoor areas.

v. **Versatility in Social Dynamics:** The verandah is a versatile space that reflects the social dynamics within a household. The verandah's openness, casual ambiance, and connectivity make it a preferred space for various activities, fostering social interactions. The verandah's unique blend of public and private elements allows it to host events ranging from intimate family gatherings to broader community functions, as shown in Images 20 and 21, highlighting its role as a socially integrative space that extend beyond their purely domestic function.

vi. **Consistency Across Diverse Orientations:** Despite differences in orientation due to microclimatic conditions, verandahs across Kutch maintain consistent use and design, as illustrated in Image 12. This adaptability to both environmental conditions and occupant preferences underscores the verandah's significance as a semi-social space hosting diverse activities beyond its domestic function.

vii. **Role of Gender Dynamics in Verandah Use:** The verandah's function shifts depending on women's involvement in household activities. Image 22 illustrates how tasks such as embroidery and social interactions shape verandah use, emphasizing its role in household gender dynamics. In conservative families, restrictions may apply, while in households with predominantly female occupants, the verandah becomes the most vibrant and dynamic space, influenced by the frequency and nature of activities.

viii. **Adaptability Across Age Groups:** The verandah's adaptability is evident among younger family members, as seen in Image 24, where it is used for various leisure activities. This dynamic use across generations highlights the verandah's continued relevance, shaped by local climatic conditions and social values, contributing to its multifunctional role.

In conclusion, this study reveals how architectural decisions, local climate, and social values shape space usage. Verandahs, as dynamic semi-public spaces, foster connection and reflect individual preferences while contributing to the broader cultural landscape. As social beings, humans transform spaces like verandahs into vibrant areas that not only enhance daily life but also strengthen social cohesion.

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Accessibility to Urban Green Spaces for Women Users: A Comprehensive Approach to Urban Planning

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Abstract—Urban Green Spaces (UGSs) play a vital role in promoting physical and mental well-being and enhancing the quality of life for urban residents. Women represent almost half the population; however, female stakeholders use the parks less than their male counterparts. Therefore, it is essential to understand how women experience and engage with these spaces. The paper comprehensively reviews issues faced by women in utilization of USGs using literature survey. It is found that safety and security, maintenance, availability of women centric amenities, overcrowding, time availability, household engagement, cultural barriers, distance from home, and unavailability of facilities remain focus of concern by women users. Multiple hypotheses investigating influence of demographic factors like age, educational qualification, monthly income, and family size on the identified issues are formulated. For investigating the influence of demographic factors on identified challenges a questionnaire survey, containing 13 items including 4 demographic items, was conducted. A total of 248 responses from January to May 2023 were analyzed using qualitative analysis and ANOVA. The ANOVA results show that variance in among the above-mentioned demographic variables except monthly income has no significant influence on the concern of women to access Urban Green Spaces. The variation in monthly income impact overcrowding and availability of time. The inferences from literature and statistical analysis recommends need for inclusive design for encouraging women in Urban Green Spaces.

Keywords: Accessibility, Urban Green Spaces, Inclusive Planning, Women, Barriers, ANOVA

INTRODUCTION

Urban green spaces are essential for improving people's health and social well-being because they provide place for leisure, recreation, and natural connection (Hartig *et al.*, 2014) (Gascon *et al.*, 2015). Spending time outside in green spaces fosters a stronger sense of local community in people (Kweon *et al.*, 1998). Exposure to green spaces not only enhance people's quality of life (Wolch *et al.*, 2014) accessibility to these spaces also lowers death rates (Wan *et al.*, 2022).

Urban green spaces protect the area's natural and cultural heritage by functioning as places for regional festivals, community events, and theatre performances (Town and Country Planning Organisation, 2014). These areas decrease the energy costs associated with cooling the buildings in cities with temperate climates (Karade *et al.*, 2017). Urban areas struggle to provide their citizens with high-quality living environments due to rapid and immense migration towards cities. Despite the manifold benefits,

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women encounter barriers in accessing and utilizing urban green spaces, stemming from safety concerns, inadequate amenities, limited transportation options, and societal norms. It is imperative to design UGSs to accommodate the specific requirements and preferences of women users, considering factors like safety, security, and diverse recreational preferences (Chong *et al.*, 2013).

Gender influences perceptions and utilization of UGSs (Cohen *et al.*, 2007) (Kaczynski *et al.*, 2010). Women are more engaged and enjoy greater aesthetic significance to UGSs than men (Veitch *et al.*, 2007). Women place more significance on the health and recreational advantages compared to males (Tyrv¨ainen *et al.*, 2007). Women are less represented and less inclined toward vigorous physical activity within urban green spaces than men (Cohen *et al.*, 2007). Males and Females have different preferences in park features based on the activities they usually perform (McKenzie *et al.*, 2016). Women are highly inclined towards the presence of walking pathways for social interaction, whereas for males, properly maintained grass and water features are of more importance from the perspective of performing physical activity (Veitch *et al.*, 2007).

The primary motivation for visiting parks, especially among female participants, was to take their children to these spaces (Kaymaz *et al.*, 2017). Women's recreational activities are highly influenced by various factors such as cultural norms, family responsibilities, age, and societal expectations (Huda & Akhtar, 2006). Safety within urban green spaces remains a focus in the concern by women (Mowen *et al.*, 2005). The preferences concerning the safety in UGSs is highly influenced by the gender (Jorgensen & Anthopoulou, 2007). The accessibility issues, demand for amenities and facilities, perception of safety and security, engagement of women in activities are influenced by age of women (Maas *et al.*, 2008) (Cohen *et al.*, 2010) (Jennings *et al.*, 2016) (Dadvand , 2016) (Sun *et al.*, 2022). Different age group requires different type of facilities (Krenichyn, 2004) (Moran *et al.*, 2020). Family size is associated with multiple responsibilities and engagement in household activities, caregiving responsibility to family members in Urban Green Spaces (Bixler & Floyd, 1997) (Floyd *et al.,* 2011). Women supervising the family members in Urban Green Spaces require open spaces with multiple activities engaging all members in nearby activities. Increase in family size increase women's responsibility specifically in Indian conditions. The access to urban green spaces, preferences of activities, desire for facilities and amenities vary with the variation in family income of women (Gordon-larsen *et al.,* 2013) (Bratman *et al.*, 2015) (Sang *et al.,* 2016). Income and accessibility need exploration in integration of UGSs and women. Self-engagement of women in earning reduces time for indulging in UGSs spaces. Education brings more awareness and thus influence the visits to Urban Green Spaces by motivation (Maas *et al.*, 2008) (Bertram & Rehdanz, 2015). Educational level influence incorporating of activities in daily schedule and type of activities, selection of UGSs for visiting and demand for amenities and availability of facilities (Krenichyn, 2004) (Mitchell & Popham, 2008) (Lee & Maheswaran, 2010) (Bertram & Rehdanz, 2015).

The planning and management of UGSs require consideration of all stakeholders. Women represents almost half of all stakeholders and have different needs in terms of safety and security, recreational preferences, lighting, quality of green spaces, overcrowding and have issues related to culture, time availability and consider intolerance as important factor. Available literature in literary form mentions all these factors being impacted by the variation in age, educational level, income and family size however statistical analysis efforts are vary scanty.

Authors explore the issue of accessibility and the factors impacting the accessibility in relation to the demographic parameters of the women user of UGSs. The investigation is helpful for urban planners, Urban Green Space planning and management authorities for decision making in considering the variations of requirements from the perspective of all women user as per their age, educational qualification, family income and family size.

Following null hypotheses were formulated to review the impact of age, educational qualification, family size and monthly income among the women respondents:

- **H1:** There is no variation in the responses related to factor impacting accessibility for women among women respondents based on their monthly family income.
- **H2:** There is no variation in the responses related to factor impacting accessibility for women among women respondents based on their age.
- **H3:** There is no variation in the responses related to factor impacting accessibility for women among women respondents based on their family size.
- **H4:** There is no variation in the responses related to factor impacting accessibility for women among women respondents based on their education qualifications.

An instrument containing 4 demography questions (Age, Educational Qualifications, Family Size, Monthly Income)

and 9 close-ended constructs using the reference of (Maas *et al.,* 2006) (Kothencz *et al.*, 2017) (Braçe *et al.*, 2021) is constructed after a systematic literature review on the topic. The respondents were asked about their age (classified in grouping of 0–20, 21–30, 31–40, 41–50, 51–60, and 60+), highest educational qualification (classified in grouping of secondary school, senior secondary school, postgraduation, and PhD), family size (in classes 1, 2, 3, 5, 6, or more), and total family income in categories of <10000, 10000-20000, 20000-50000, 50000-1Lakh, 1 Lakh to 10 Lakh, and 10 Lakh plus. The Likert scale is frequently used to assess the respondents' attitudes by inquiring about their agreement or disagreement with an asked statement or question in various studies (Kothencz *et al.*, 2017). Five-point Likert scale (1-5; 1- highly disagree; 5 highly agree) is used for collecting the responses from women users of the urban green spaces. Literature review pointed out that safety and security, quality of green spaces, lighting facility, facilities for all stakeholders, overcrowding, poor maintenance, cultural issues, unavailability of time, and history of intolerant event (case of eve teasing, harassment, and molestation in the green spaces) remain major concern among female for accessing the urban green spaces. These constructs specifically targeted the factors influencing the Urban Green Spaces usage by women users. The questionnaire includes a general introduction question, demographic questions and women's perspective on urban green spaces accessibility. The investigators collected 260 responses by randomly surveying women in Sonipat, Delhi, Chandigarh, Jaipur, Palwal, Faridabad, and Rohtak. The survey was conducted from January to May 2023. A total 248 responses were finally filtered for analyzing the issues of women related to urban green space usage. Demographic analysis of the 248 responses followed by One-way ANOVA is used to test the relationship between the demographical characteristics of women's and their responses of green space accessibility.

Demography of the Respondents

The results of demographic criteria related to age, highest educational qualification, family size and total family income) in the classification mentioned is presented in Figure 1(a, b, c, d).

The age of the 248 female respondents is classified in the grouping of 0–20, 21–30, 31–40, 41–50, 51–60, and 60+. Among the respondents of the questionnaire 34 (14%) were between the ages of 0 and 20, 98 (39%) were between the ages of 21 and 30, 34 (14%) were between the ages of 31 and 40, 42 (17%) were between the ages of 41 and 50, 30 (12%) were between the ages of 51 and 60, and the remaining 10 (4%) were over 60. This implied that the responders are representative of a broad spectrum across various age groups and have almost uniform distribution.

The results of the responses on highest educational qualification show that 56 (23%) respondents had completed their graduation, 78 (31%) respondents had a post-graduate degree, 21 (9%) were enrolled in or had finished their doctoral programme, 50 (20%) had completed senior secondary school, and 43 (17%) had only completed secondary school. The findings demonstrate that the female respondents indicate a more educated population and have a greater range of educational backgrounds.

The results of survey regarding family size of respondents show that 89 (36%) of the respondents belonged to a family with four people, 76 (36%) to a family with five members, 43 (17%) to a family of six plus, 24 (10%) to a family of three members, 9 (3%) to a family of two members, and 3% of the female respondents are single and do not have a family. The results indicate that a wide range of family sizes were represented in the poll.

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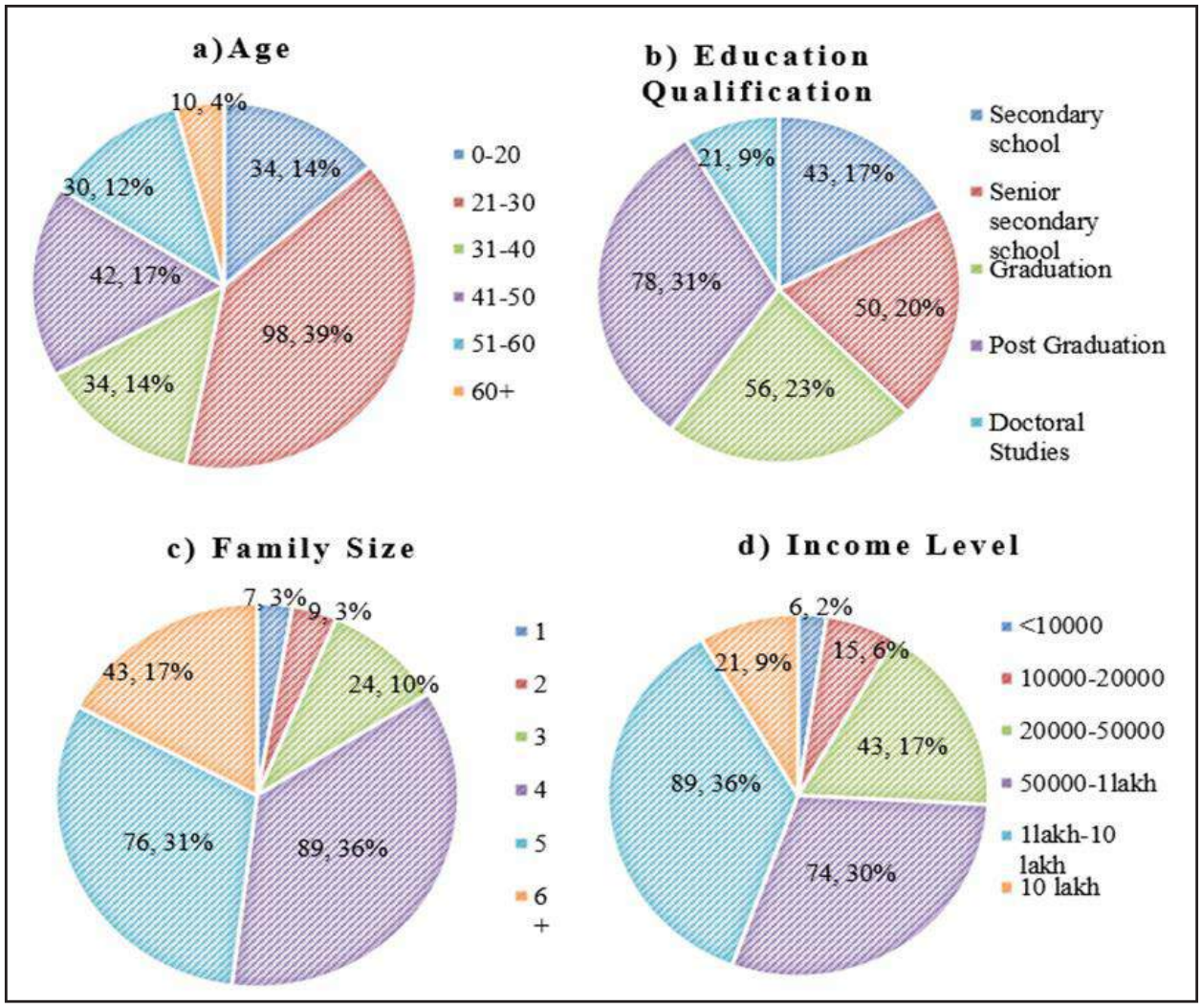

Fig. 1: Demographic Profile categorization of the Women Respondents based on the a) Age, b) Educational Qualification, c) Family Size, d) Income Level

represented in the poll. The responses about their total family income in categories of <10000, 10000-20000, 20000-50000, 50000-1Lakh, 1 Lakh to 10 Lakh, and 10 Lakh plus indicate the approximate monthly income of all the family members of respondents (Figure 4). 89 (36%) people lay in the group of 1 to 10 lakh income, 74 (30%) had 50,000 to 1 lakh income, 43(17%) had 20,000 to 50,000 thousand, 21 (9%) belonged to the group of 10 lakhs income, whereas 15 (6%) had 10,000 to 20,000, and the remaining 6 (2%) came from the group of less than 10,000. The distribution of respondents among the different economic classes shows that women respondents are representatives of all economic classes.

DESCRIPTIVE ANALYSIS OF THE RESPONSES

The results of the survey on the factors influencing the decision of women users on usage of Urban Green Spaces show that range of mean of responses ranges from 3.28 to 4.06, standard deviation ranges from 0.982 to 1.114, the data is negatively skewed with low kurtosis values. This shows that the responses are much aligned towards the issues raised and respondents agree or highly agree to the issues being faced in using the Urban Green Spaces.

The responses regarding questions on five-point Likert scale regarding quality of UGSs, safety and security, lighting

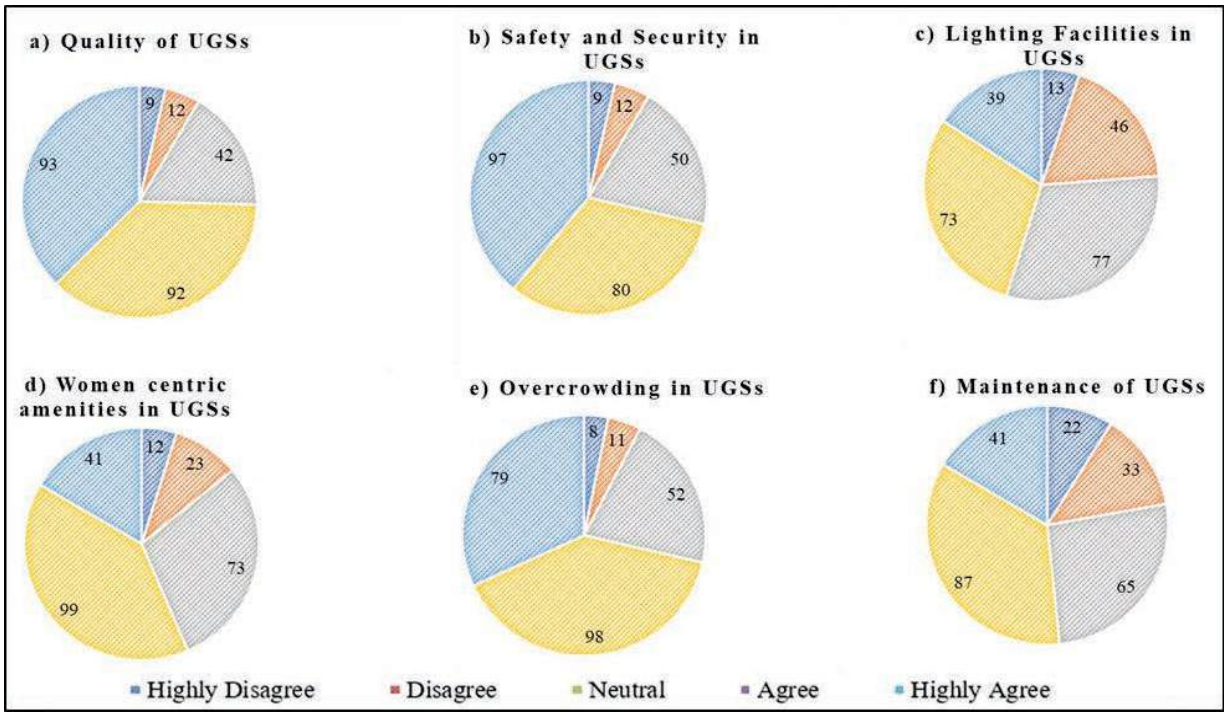

Fig. 2: Women respondent's opinion regarding a) quality of UGSs, b) safety and security, c) lighting facility in USGs, d) women centric amenities, e) overcrowding, and f) maintenance through pie charts on five-point Likert Scale

facility in USGs, women centric amenities, overcrowding and maintenance are presented through pie charts in Figure 2 a, b, c, d, e, and f respectively. Quality of Urban Green Spaces is an important factor influencing women's decision in using the green space. More than 75% of the women respondents agreed to the quality of spaces being important factor influencing the usage. More than 70% of the women respondents have agreed / strongly agreed that security and safety influence their decision on usage of Urban Green Spaces. The response of female respondents regarding lighting influencing their decision on usage of Urban Green Spaces show centrality in their responses which may be due to the usage being limited to daytime hours. However, the limited frequency of women users in non-natural light hours strongly show that women highly regard availability of lighting facilities in Urban Green Spaces. Out of the 248 women respondents 173 respondents feel that non availability of women centric amenities discourages the women users from using the Urban Green Spaces which means that inclusive planning of Urban Green Spaces should strongly include women users in planning, management and maintenance issues. Under crowding and overcrowding both are regarded as negative aspects for women users using UGSs. More than 75% of the women respondents prefer not to use the overcrowded Urban Green Spaces. Maintenance of Urban Green Spaces is considered highly important factor with more than 80% of the respondents of the present survey validating the same.

The responses regarding questions on five-point Likert scale regarding cultural issues of the respondents, history of intolerant events in Urban green Spaces and Unavailability of time with respondents are presented through pie charts in Figure 3 a, b, and c respectively. The responses regarding cultural issues of respondents show that cultural issues bind the women showing using Urban Green Spaces however the increase in education level has lesser influence in urban areas. More than 80% of the women respondents prefer to avoid using the Urban green Spaces with history of intolerant events. All users in general also try to avoid such spaces. Unavailability of time with the respondents due to their engagement in other activities. The responses of the survey validate this item with approximate 200 respondents out of 248 respondents.

Attention to the above-identified issues, which affect the accessibility and use of green space, will lead to improved

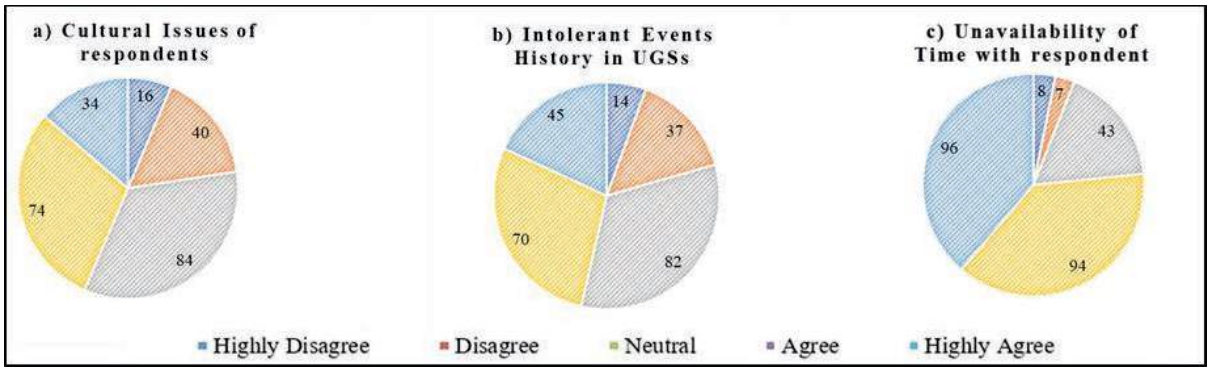

Fig. 3: Distribution of responses regarding a) cultural issues of the respondents, b) history of intolerant events in Urban green Spaces and c) Unavailability of time with respondents through pie charts

women's participation and visitation in urban green spaces. The results of the survey show that there might be strong variation in factors influencing the usage with the variation in age, family size, family income and educational level of the female respondents, hence a relationship analysis should be conducted for establishing the causality in the responses.

Relationship Analysis Based on ANOVA

The proposed hypotheses for age, educational qualification, family size, and monthly income are tested using an ANOVA connection analysis. The

following heads display the results according to these variables.

Monthly Income

The quality of green spaces was assessed between groups. The results showed that there was no statistically significant difference in the

group means (Sum of Squares = 2.096, df = 5, Mean Square = 0.419, F = 0.387, p = 0.857). Additionally, there was no statistically significant difference in the group means for Lighting Facilities, Facilities for All Stakeholders, Poor Maintenance, Cultural Issues, and History of Intolerant Events, indicating that these characteristics had no effect on the accessibility to green spaces in relation to monthly income.

Whereas security and safety between groups with Mean Square = 2.738, F = 2.526, p = 0.030, Sum of Squares = 13.689, df = 5, Sum of Squares = 13.732, df = 5, Mean Square = 2.746, F = 2.867, p = 0.016 for overcrowding and Sum of Squares = 16.572, df = 5

Mean Square = 3.314, F = 3.621, p = 0.004 for time

unavailability with across groups proved to have an impact on how often women use green spaces because
the groups' means differ significantly. Table 3 displays the ANOVA results for the association between monthly income and all responses on the instrument's theoretical constructs.

Family Size

Significant correlations between family size and factors such as the quality of green areas, safety and security, facilities for women stakeholders, overcrowding, poor maintenance, lack of time, and history of intolerant events were found. The non-significant ($p > 0.05$) F-statistics show that there are no statistically significant differences in the group means for any of the assessed variables. Hence, the null hypothesis cannot be rejected.

Age

The quality of green spaces, safety and security, lighting facilities, facilities for all stakeholders, overcrowding, poor maintenance, cultural issues, time issues, and past incidents of intolerant events are among the examined variables for which the F-statistics are not significant ($p > 0.05$). This indicates no statistically significant differences in the group means for any variables. These results do not support the rejection of the null hypothesis.

Table 1: The results of ANOVA for Relationship among Monthly Income and all Responses on Theoretical Constructs of the Instrument

		Sum of Squares	df	Mean Square	F	Sig.
Quality Green Spaces	Between Groups	2.096	5	.419	.387	.857
	Within Groups	261.904	242	1.082		
	Total	264.000	247			
Safety and Security	Between Groups	13.689	5	2.738	2.526	.030
	Within Groups	262.247	242	1.084		
	Total	275.935	247			
Lighting Facilities	Between Groups	4.545	5	.909	.740	.594
	Within Groups	297.290	242	1.228		
	Total	301.835	247			
Facilities for all Stakehoders	Between Groups	2.057	5	.411	.384	.860
	Within Groups	259.540	242	1.072		
	Total	261.597	247			
Overcrowding	Between Groups	13.732	5	2.746	2.867	.016
	Within Groups	231.812	242	.958		
	Total	245.544	247			
Poor Maintenance	Between Groups	6.619	5	1.324	.967	.439
	Within Groups	331.252	242	1.369		
	Total	337.871	247			
Cultural Issues	Between Groups	2.555	5	.511	.424	.832
	Within Groups	191.687	242	1.205		
	Total	294.242	247			
Houschold engagement	Between Groups	16.572	5	3.314	3.621	.004
	Within Groups	221.521	242	.915		
	Total	238.093	247			
History intolerant enents	Between Groups	3.368	5	.674	.538	.748
	Within Groups	303.241	242	1.253		

Educational Qualifications

There is no statistically significant difference in the group means for all the variables, as indicated by the F-statistics ($p > 0.05$). In contrast, the only variable that significantly varies between the groups is Overcrowding (Mean Square = 3.115, F = 3.248, p = 0.013; Sum of Squares = 12.460, df = 4).

RECOMMENDATIONS

Based on the inferences following are recommended considering the significance of the conclusions drawn from the literature and the mixed method approach used to analyze the survey instrument results:

- Women will use urban green areas more if planned for and maintained inclusively.
- Maintaining the quality of green spaces is necessary to increase their use by all urban residents.
- Women's participation in urban green areas will rise with the implementation of safety and security measures.
- Adding lighting to urban green spaces will encourage female users to use them at times other than during the day.

- Women's participation in urban green spaces will increase with the proper installation of amenities, regular maintenance, and additional facilities for them.
- Adding urban green spaces can prevent crowding and attract more female users.
- Increased levels of education will reduce cultural constraints on women's use of urban green spaces.
- Fixed working hours and engagement of all users may lead to a rise in the number of women in urban green areas.

CONCLUSION

UGSs are essential to living beings as they have many pragmatic impacts and serve many functions in today's rapidly changing urban world. Despite having many benefits, women are observed to use green spaces less due to different barriers. Hence, studying and gaining insights into women's opinions and experiences with UGSs is necessary. So, an extensive study has been carried out on the barriers women experience while using UGSs. A mixed-methods approach, including a questionnaire survey containing 13 items, including 4 demographic items, was conducted to examine the barriers faced by women in accessing UGSs. Results showed that women's access to urban green areas could be increased by improving and implementing necessary safety and security measures, raising with the implementation of safety and security measures, providing basic amenities and facilities for women stakeholders, managing overcrowding, and considering cultural and personal issues. Depending on the monthly earnings of women, perceptions of the factors affecting their accessibility differ substantially.

CONFLICTS OF INTEREST

No conflict of interest was declared by the authors.

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Street Network Configuration: A Criterion to Assess Walkability Potential of a Traditional and Modern Settlement in Chennai, India

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Abstract—Walking is a physical activity that comes with numerous health benefits. The walkability of a built environment is influenced by the spatial characteristics of the street network. Traditional organic settlements and planned contemporary neighborhoods have different spatial configurations, which affects their walkability potential. In this study, two urban settlements, in Chennai, Tamil Nadu, namely, Triplicane and Anna Nagar were analyzed to determine their walkability potential. The study involved space syntax analysis using DepthmapX to evaluate the syntactic values of connectivity, integration, intelligibility, and synergy of the street network in both areas. The findings of the study were validated through on-site evaluation. The research revealed that both settlements had varied levels of connectivity and integration. The study concluded that the walkability potential of a neighborhood is not only dependent on the spatial characteristics of the street network, but, also on the objective site conditions, microscale-built environment attributes, and walkability barriers.

Keywords: Walkability, Street Configuration, Space Syntax, Walking, Connectivity, Integration

INTRODUCTION

Walking is the most sustainable mode of transportation and a healthy physical activity (Fonseca *et al.,* 2021). Walkability refers to the potential of the built environment's influence on people to walk to different destinations and purposes (Garau *et al.,* 2020). This is mainly influenced by the street network, its spatial characteristics and linkages (Molaei *et al.,* 2021). Indeed, a rapidly growing body of literature has recognised the importance of street characteristics like connectivity (Hajrasouliha & Yin, 2014), compactness (Cervero & Kockelman, 1997) and proximity (Lee & Moudon, 2004) on walking behaviour and the choice of walking as a mode of commute. The street network configuration and the corresponding walkability levels can vary between a traditional organic settlement and a modern planned neighbourhood. Evidence suggests that spatial configuration is a vital correlate of walking in the Space Syntax theory. Space syntax explores the association between human societies and space (Bafna, 2003). This method has been widely used to explore the spatial characteristics of street networks in developed countries (Farzadi Moghadam, 2018; Hajrasouliha & Yin, 2014; Paraskevopoulos *et al.*, 2020). Despite such comprehensive studies in developed

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countries, insufficient work has been carried out to examine the spatial configuration of street networks in developing countries.

In summary, there are several gaps in the literature that this study aims to address: (a) there is a dearth of studies that analysed the spatial network configuration and its impact on walkability levels in developing countries like India; (b) comparative analysis of the spatial structure of the street network in a traditional and a modern settlement and its impact on the walkability potentials were rarely explored together in the same study; (c) Until recently, only a few studies have used the space syntax methodology to identify and evaluate street segments with poor connectivity and integration that require immediate attention to enhance walkability.

This paper comprises five sections. Section two presents the theoretical background of the research explaining that street spatial structure correlates with walkability. The third section discusses the study area selection criteria, the data used and the methodological framework adopted. The fourth section presents comprehensively the results obtained by comparing the spatial network configuration in the traditional and contemporary settlement and their corresponding walking potentials. The streets have been ranked based on their capacity to attract pedestrian movement. Furthermore, street segments with poor connectivity and integration have been identified, evaluated and recommended for immediate action. Finally, the conclusion section summarises the findings of the research, their implications, and the scope for further research.

Walking is the most elemental and primitive form of urban mobility, that enables people to move around to reach destinations and experience urban spaces (Millan, 2009). It is the most sustainable and safe mode of transport and does not require any equipment (Hart, 2009). The benefits of walking have been well documented in previous studies. WHO recommends at least 150 minutes of weekly physical activity in adults and older adults to achieve healthy and active ageing (WHO, 2011). Major benefits of walking include good health (physical, mental and social well-being), environmental protection (reduces carbon footprint and traffic congestion), enhanced social cohesion, economical as a mode of commute and results in habitable communities (Blaga, 2012; Litman, 2013). In the 2030 Agenda for Sustainable Development and the associated New Urban Agenda, the UN has stressed the importance of creating accessible environments and improving walkability. Walking is so vital that it contributes to the four Sustainable Development Goals (SDG) in a big way – SDG 3 (Good health and well-being), SDG 7 (Affordable and Clean Energy), SDG 11 (Sustainable cities and communities) and SDG 13 (Climate Action) (UNDESA, 2023).

The built environment must be conducive to make the walking episode a pleasant experience. This makes the environment walkable. Walkability is an umbrella term that has been given several connotations. Forsyth & Southworth defined walkability as the characteristic of an urban area that promotes physical activity. It is a built environment that is located near essential destinations, has no barriers, is secure, and has proper pedestrian infrastructure and green spaces (Forsyth & Southworth, 2008). This concept is also mentioned in the seminal work of Wang & Yang (2019) as a type of accessibility that provides comfortable walking in a specific area and reaching destinations on foot. The association between walkability and city streetscapes provided a better ambiance for people to take up physical activities like exercise, leisure or recreation. (Wang & Yang, 2019).

The design of street networks, their connectivity and configuration have a vital role to play in attracting people to walk and improving the walkability rate (Sdoukopoulos *et al.*, 2017). Connectivity indicates the spatial relationship between streets in a network. It explains the availability of alternative routes, that can attract or repel pedestrian usage to reach a destination (Nyunt *et al.*, 2015). In comparison, integration explains the cognitive complexity of reaching a street. It shows how a street segment is integrated or segregated from the network (Baran *et al.*, 2008).

Space Syntax Theory and analytical methodology were developed by Bill Hillier and his colleagues in the year 1989 (B. Hillier & Hanson, 1989). Space Syntax is a mathematical model for street networks based on the Graph Theory to calculate "spatial topological relationships". It provides a theoretical basis and methodology that explains and quantifies the spatial correlates of the built environment and their impact on socio-economic activities (Van Nes & Yamu, 2021) This theory derives its roots from the Graph Theory and the Theory of Natural Movement. Space Syntax considers how each space is connected to all other spaces by directional and angular changes in the spatial system. It measures the to-movement (closeness) and through-movement (betweenness) potentials of every street segment to all other segments in the network (B. Hillier, 1999; W. R. G. Hillier *et al.*, 2012).

In Space Syntax streets are represented in the form of axial maps and segment maps. An axial map has a minimum number of axial lines which represent the longest line of sight for movement (the way humans move linearly in urban street networks) in a set of convex spaces. Segment maps are obtained by splitting the axial lines at junctions and account for the change in direction from the origin to the destination (Turner *et al.*, 2005; Van Nes & Yamu, 2021). A well-connected street network contributes to better walkability by providing many potential route choices and easy access to more destinations (Jiang & Liu, 2009). It is a static local dimension that includes all the direct links a street has with other streets located in its proximity. Thus, a street with many connections to its neighbouring streets is said to have high connectivity value and vice versa.

Connectivity is calculated using one-step analysis or two-step analysis based on the scale of the area to be analysed (B. Hillier & Hanson, 1989; Van Nes & Yamu, 2021). Integration indicates the ease with which one can reach a particular line in an axial map. Mathematically, it is expressed as an algebraic function of the number of axial lines that must be crossed to move from one axial line to the other in an axial map. The higher the integration values lower the number of axial lines to be traversed. The global integration [HH] of a street or axial line is the degree of accessibility of a street to all other streets in the entire urban system under study. Local integration [HH]R3 is the degree of accessibility of a street to another street within a specific syntactic radius, 3 in this case. It shows show how each street is connected to its vicinity in terms of three times direction changes. The axial line with the highest value of global integration is the street that can be accessed from all other streets with minimal change in direction (Baran *et al.*, 2008; B. Hillier & Hanson, 1989).

MATERIALS AND METHODS

This section is divided into (a) a brief introduction of the two study areas; and (b) the methodology used for the analysis. A diagrammatic representation of the methodology is depicted in Figure 1.

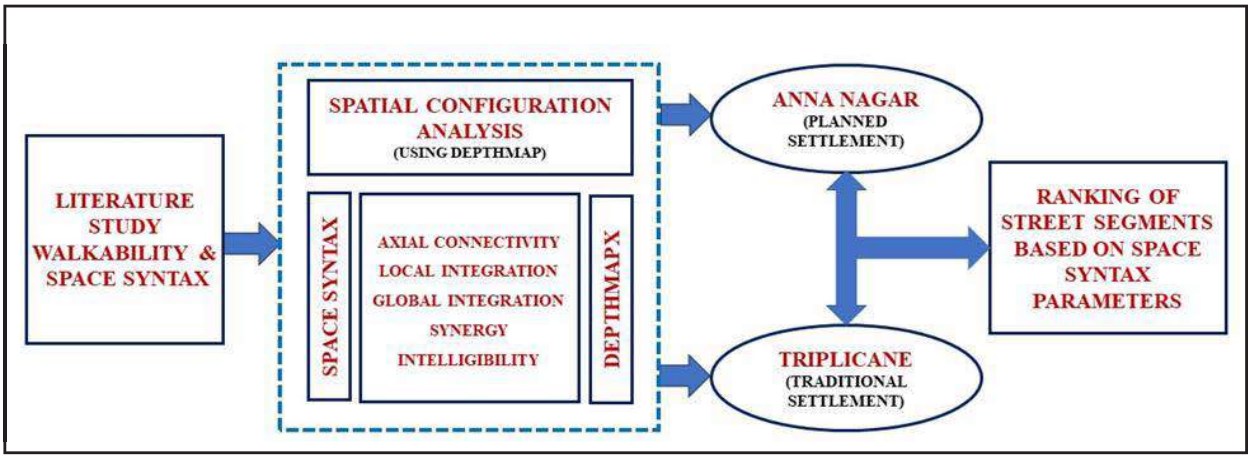

Fig. 1: Conceptual Framework (*Source*: Author)

STUDY AREA

The study is based in the Chennai Metropolitan Area (CMA) that comprises 15 zones and is further subdivided into 200 wards. The study areas (Figure 2) are Triplicane (Ward No. 116) and Anna Nagar (Ward No. 101) in Chennai, Tamilnadu, India. Triplicane is a traditional organic settlement located in South Chennai while Anna Nagar is a planned settlement located in the Central part of Chennai. These study areas were chosen to compare the layout of street networks and their walkability potentials in two neighborhoods with vastly different spatial characteristics. Moreover, these areas possess attraction poles like neighbourhood parks, beaches and places of worship which are of heritage importance.

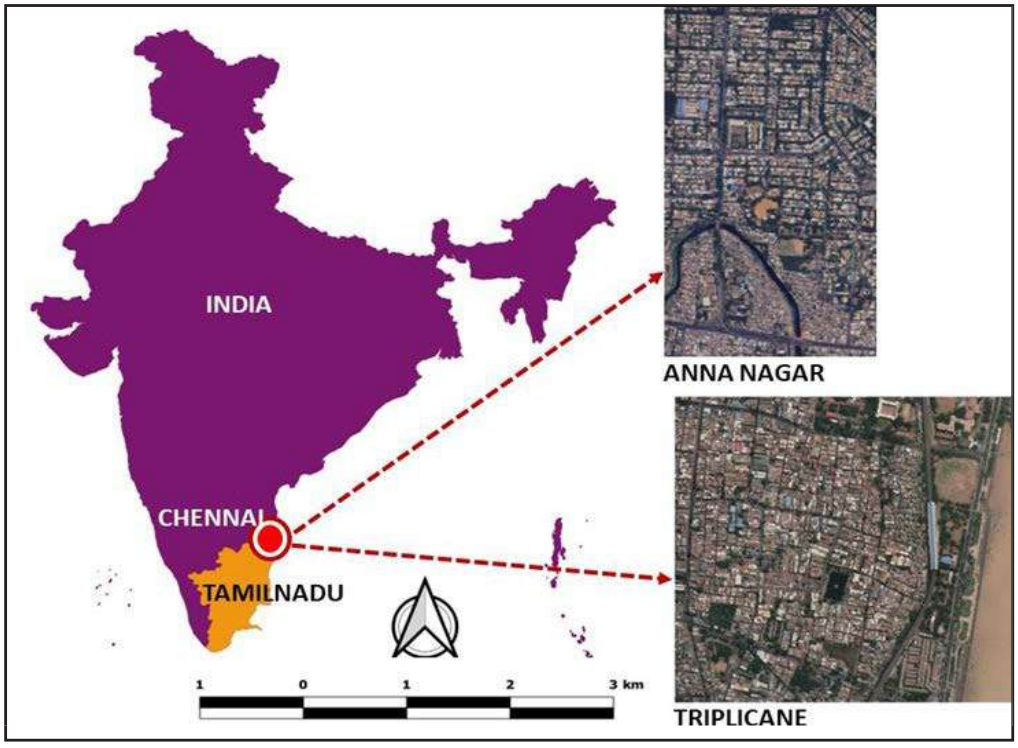

Fig. 2: Map showing the location of Triplicane and Anna Nagar in Chennai, Tamil Nadu, India.
(***Source***: Google Earth Software modified by Author)

SPACE SYNTAX ANALYSIS

The study utilised Space Syntax to examine the spatial character of the street network in the two study areas. The analysis focussed on the topological characteristics of the streets, their connectivity, and their accessibility in a network. In a space syntax map, each street is represented by an axial line which is the longest line of vision in a street. In this study, the space syntax analysis was done using the DepthmapX software. This software is user-friendly and has fast data processing capabilities. It presents an immediate visualisation of the hierarchy of streets based on their spatial character. The connectivity and integration values of the streets are visually depicted with a graduated colour symbology. Higher values are represented by warm colours like orange or red and lower values are represented by cool colours like blue or green.

Two different space syntax methods were used in the analysis, namely connectivity and integration. The connectivity of any axial line is the number of lines that directly intersect the axial line under study. If more lines intersect a particular axial line, it is marked with a higher connectivity value, denoted on maps by warm colors such as red. The implication of an axial line having a high connectivity value is that it has high access potential to a large number of axial lines or streets in the network. Integration aids in understanding how close the place of origin is to all other axial lines in the network. This is calculated at two levels, Global Integration (at radius = n) and Local Integration (at radius = 3). High integration from the topological standpoint refers to a space that can be easily accessed and hence is well integrated. Intelligibility explains the correlation between axial topological integration (R=n) and axial topological connectivity. A value of high intelligibility implies a strong correlation between these two indices and it marks the strong relationship between the entire urban space under consideration and the elements that make up the system. Synergy is the correlation between the axial topological integration values at the global level and the local level. This explains the degree to which the parts of the spatial system refer to the global or the entire system in which it is located.

RESULTS AND DISCUSSION

The syntactic properties were evaluated using space syntax analysis in both areas. The analysis yielded syntactic

measures like connectivity, local integration, global integration, intelligibility and synergy. The main parameters of the space syntax analysis of the two areas from an all-line axial map are presented in Table 1. Triplicane (Figure 3), a traditional settlement, 3337 axial lines constitute the street network. In terms of connectivity, the number of possible street connections a street can have may range between 6 and 411. However, the streets with more connections are the main roads like the Dr. Besant Road, Pycrofts Road and the Venkatarangam Pillai Street. This explains high level of accessibility along these street segments. The streets with more connections are marked in red and the ones having the least connectivity are depicted in blue.

The calculation of network centrality was done at the global and local scales. Axial integration was computed for two topological radii namely, R=n for analysis conducted at the global scale (Global integration) and R=3 for analysis conducted at the local level (Local Integration) (Refer Table 1). The broad and extensive main roads, like Dr. Besant Road, Pycrofts Road and Venkatarangam Pillai Street showcasing enhanced connectivity, demonstrated substantial global integration. Similarly, on a local scale, wide and elongated streets exhibited superior integration metrics in contrast to their narrower, dead-end counterparts. The heightened local integration within the vicinity inclusive of Dr. Besant Road, Venkatarangam Pillai Street, and Canal Street establishes a primary pedestrian thoroughfare, thereby contributing to enhanced walkability within the community.

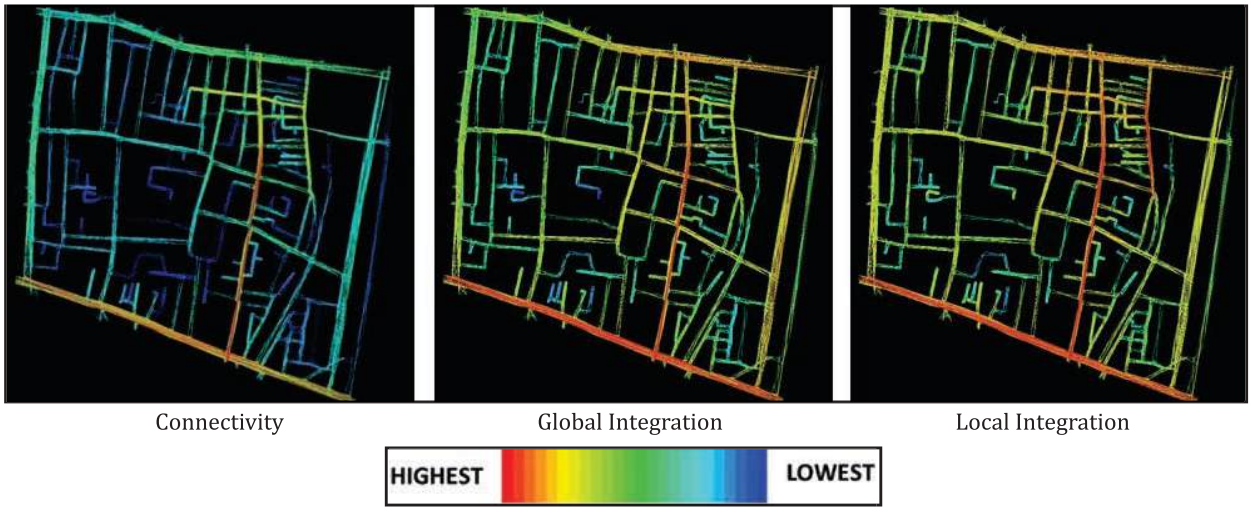

Fig. 3: Map showing Space Syntax Analysis of Triplicane, Chennai, Tamil Nadu. (***Source:*** Author)

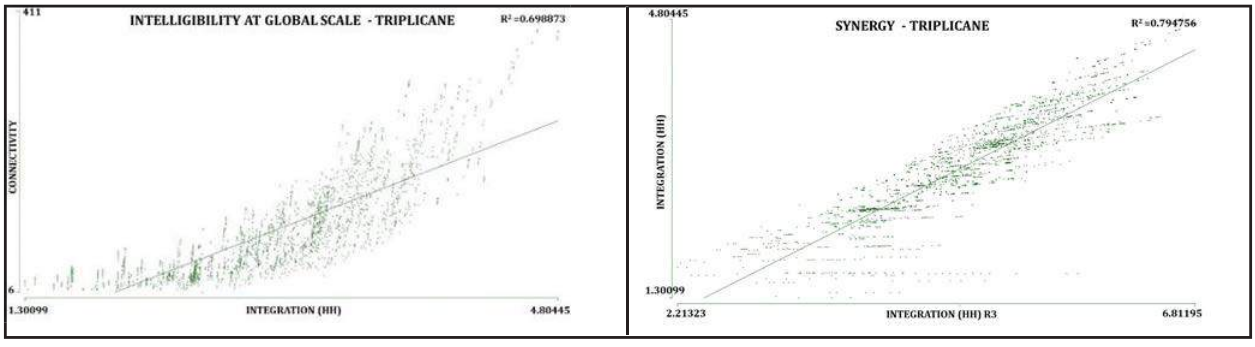

Fig. 4: Intelligibility and Synergy values of Triplicane, Chennai, Tamil Nadu. (***Source***: Author)

In Space syntax the intelligibility of a space explains the level of correlation between the local space and the entire spatial system. The R2 value of intelligibility that falls within a range of 0–0.5, indicates weak spatial identifiability. A value of R2 between 0.5–0.7 signifies good spatial identifiability, while a range of R2 between 0.7–1.0 signifies strong spatial recognizability (Xu *et al.*, 2020) The intelligibility value of Triplicane (Figure 4) shows a linear correlation between the axial connectivity and Global Level Integration with an R2 value of 0.698873. The value indicates that the visibility of the street axis of the block is good. The intelligence value in Triplicane suggests that pedestrians can more easily discern the overall spatial structure from local perception, leading to increased spatial intelligibility.

The synergy value is described by a linear regression index of the local integration degree (R3) and the global integration degree (Rn). A higher synergy value signifies easier spatial recognition and stronger axial synergy. Typically, values ranging from 0.5 to 0.7 are utilized. A value below 0.5 indicates poor synergy, while a value surpassing 0.7 denotes good synergy. Triplicane exhibits a synergy value of 0.794756. The calculated value surpasses the maximum value of 0.7, signifying a high level of synergy and a well-established spatial interaction between the local area and entire neighbourhood. This suggests that pedestrians can easily comprehend the overall spatial layout through the local streets and alleys , thus contributing to better walkability.

In Anna Nagar (Figure 5), the planned settlement, 5121 axial lines constitute the street network in the fewest line axial map. In terms of connectivity, the number of possible street connections a street can have ranges between 4 and 918. The streets in this study area follow a spatial hierarchy of avenue roads, main roads, local streets and service lanes. The streets higher up in the hierarchy have higher connectivity than the local streets. The 3rd Avenue Road, which is a central spine runs across the entire neighbourhood has the highest connectivity. The streets with more connections are marked in red and the ones having the least connectivity are depicted in blue.

Axial integration performed at the global level showed greater integration surrounding the 3rd Avenue Road, one of the longest and widest in the settlement. Here the streets are of gridiron pattern meeting at right angles. Local integration is also higher near the 3rd Avenue Road, 6th main road, 5th main road and 2nd Avenue Road. In Anna Nagar, the scatter plots for Intelligibility and Synergy show a linear correlation with high R2 values of 0.699646 and 0.806673 respectively (Figure 6). The elevated levels of intelligibility and synergy

Fig. 5: Map showing Space Syntax Analysis of Anna Nagar, Chennai, Tamil Nadu. (***Source***: Author)

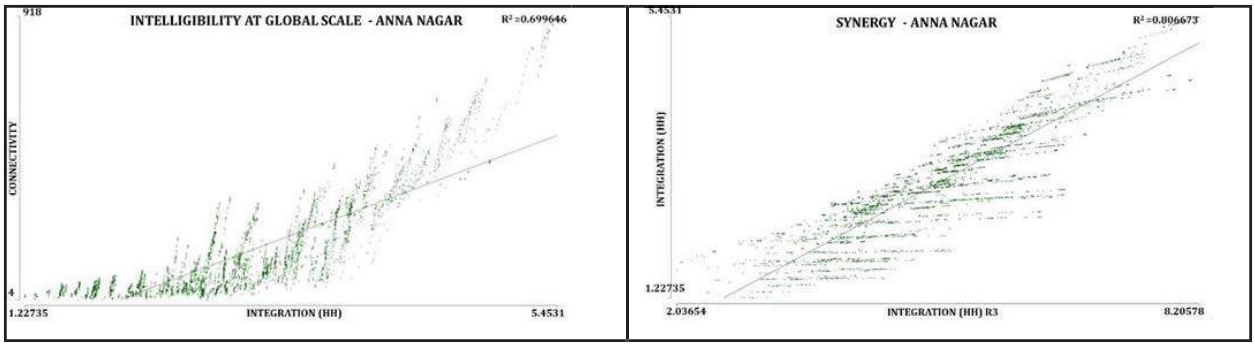

Fig. 6: Intelligibility and Synergy values of Anna Nagar, Chennai, Tamil Nadu. (***Source***: Author)

in Anna Nagar can be ascribed to the structured hierarchy of road networks, which encompasses avenue roads, main roads, and local streets. The adherence to a grid iron pattern by the streets enhances legibility and spatial cognition, thus augmenting the walkability potential of the neighborhood.

On comparing the two study areas, Anna Nagar is well connected when compared to Triplicane. In terms of Global Integration, Triplicane has higher integration than Anna Nagar. This implies that most destinations in Triplicane are easily accessible by walk. However, in the context of local integration Anna Nagar is well integrated than Triplicane providing more scope for walking. Anna Nagar being a planned settlement, has many pedestrian thoroughfares encouraging more walkability and access to local destinations.

Table 1: Syntactic Parameters of the Two Study Areas

Sl.	Space Syntax measures	Triplicane	Anna Nagar
1	Connectivity		
	Minimum	6	4
	Average	87.2223	147.243
	Maximum	411	918
2	Global Integration [HH]		
	Minimum	1.30099	1.22735
	Average	2.85179	2.92352
	Maximum	4.80445	5.4531
3	Local Integration [HH] R3		
	Minimum	2.21323	2.03654
	Average	4.6184	5.08243
	Maximum	6.81195	8.20578
4	Intelligibility	0.698873	0.699646
5	Synergy	0.794756	0.806673

This study is further supplemented with the on-site assessment, which throws light on the other parameters like street width, sidewalks, presence of barriers to walking and road conditions.

Triplicane is an old settlement with high density. The on-site survey in Triplicane, revealed that most streets were narrow lanes and had no sidewalks. On the contrary, the main roads with high connectivity and integration, had sidewalks on both sides. In the narrow lanes, the pedestrians were compelled to walk on the carriageway, which had projecting manholes, uneven speed bumps without markings and intrusion of stray cattle (Figure 7). In some specific cases like Dr. Besant Road and Pycrofts road, the sidewalks were encroached by streets vendors, eateries and parked vehicles, making them inaccessible to pedestrians.

Fig. 7: Barriers to Walking in Triplicane, Chennai, Tamil Nadu. (***Source:*** Author)

Fig. 8: Barriers to Walking in Anna Nagar, Chennai, Tamil Nadu. (***Source*:** Author)

Anna Nagar is a planned settlement with lesser density and a gridiron pattern of street network. The streets were categorized as avenues, main roads and local streets. Though the shaded avenues provided a pleasant walking experience, they had certain shortfalls. The sidewalks in the avenues and main roads had walkability barriers like parking lots abutting sidewalks, uneven sidewalks, trees, electrical transformers and hawkers (Figure 8). Anna Nagar is known for its high car ownership rate per household. Thus, residents park their cars in residential streets, posing a hindrance to pedestrians.

CONCLUSION

This study investigated the relationship between street configuration and walkability potentials in two different neighbourhoods in Chennai, Tamil Nadu. The study utilised Space Syntax as a research tool, to identify streets, that are well connected and integrated and hence their walkability potential. The results were confirmed through an on-site survey that examined the actual site conditions. The findings showed that the two areas, Triplicane and Anna Nagar, with contrasting spatial configurations, exhibited varied connectivity and integration values. This method had some limitations, though. This evaluation procedure was primarily based on the geometric and topological configuration of the street network. Thus, streets were categorised as well connected and integrated, but, it did not reflect the important on-site conditions which impact walking behaviour and walkability. For example, the width of streets, sidewalk availability and continuity, traffic conditions and pedestrian safety levels also have a bearing on the walkability of a built environment. To arrive at holistic outcomes and recommendations for developing long-term planning strategies, the space syntax methodology should be combined with on-site evaluation studies that consider microscale-built environment factors.

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Urban Neighbourhood Outdoor Environments and Age-friendliness: A Study of Jaipur City, India

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Abstract—An age-friendly built environment is crucial for older adults to retain an active lifestyle, impacting their ability to independently execute all their daily activities in out-of-home settings. The availability of public spaces within outdoor environments is often associated with improving social inclusiveness and additional health benefits. The aspect of an outdoor built environment for geriatric populations to enjoy good health and well-being remains under-studied in the context of Indian cities. Therefore, the study attempts to understand the key challenges experienced by older adult populations towards their daily life activities in the outdoor built environment in Indian cities. The study hypothesized that the quality of neighbourhood public and green open spaces, along with the accessibility to such outdoor spaces, strongly impact the overall satisfaction level of older adults. A mixed method approach has been adopted to conduct the study, incorporating observational analysis and surveys administered among the urban older adult populations. Survey schedules were carried out among randomly selected older adult residents aged 60 years and above (n =70) in and around the urban neighbourhoods in Jaipur city. Correlation analysis and regression analysis were conducted on the responses from the older adults. Findings indicate that accessibility barriers and safety concerns from traffic negatively impact the satisfaction and active ageing among elderly residents within the out-of-home neighbourhood environment. Creating age-friendly neighbourhood spaces and improving the accessibility linkages between the home and the outdoor built environment through architecture and design interventions can help improve user experiences and life satisfaction among the ageing population.

Keywords: Outdoor Environments, Age-friendliness, Well-being, Public Open spaces

INTRODUCTION

Population ageing has become an evident demographic future in many developed nations and is projected to be a reality for many developing nations, including India, in the forthcoming decades. As the percentage of older adults in the global population expected to increase from 10% in 2022 to 16% by 2050, a considerable segment of this cohort is believed to be confronted with health-related challenges and disabilities for an extended period due to frailty and

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diminished muscular strengths. Such demographic trends call for developing social, physical, and environmental infrastructures to support the specific needs of ageing populations and help them maintain healthy lifestyles (Steels, 2015). While various researchers establish health, age care and financial aspects as essential aspects for life satisfaction among older adults, a conducive neighbourhood and city-built environment is essential to enhance opportunities for active ageing and social connectedness among older adults.

Supporting ageing from different perspectives has received focus from the United Nations and other international bodies since 1982. World Health Organization has been propagating the idea of Age-friendly cities since 2007, which focuses on the lives of older adult populations and their living environment for enhancing health, care, social inclusion and participation (WHO, 2007). The 2030 agenda for Sustainable development focuses on developing sustainable cities and communities. With a focus on creating age-friendly environments, the United Nations has declared the decade from 2021 to 2030 as the decade of healthy ageing.

Nuclear family structures have become the contemporary realities of our societies in the wake of migration and urbanization, thus leaving behind older adult populations and enhancing stresses experienced by the individuals who cross an age of 60 years and above towards maintaining independent outdoor functional abilities to carry out most basic Activities of daily life (ADL). As people age, most develop health disorders associated with diminished cognitive and physical capabilities characterized by decreased muscular strength and disturbed gait concerns. As such, it becomes pertinent for planning bodies and policymakers to work towards creating age-friendly outdoor spaces in a neighbourhood-built environment, which becomes the first point of outdoor contact to provide a supportive living environment for the ageing population towards maintaining social connectedness and independent mobility. The research attempts to explore and investigate a few research questions: a) What outdoor activities are considered necessary by older adults in their daily routines? (b) What are the various challenges experienced by older adults towards their independent functioning and active ageing in outdoor spaces in Jaipur city?

With an emphasis on the strategic development of urban neighbourhoods and city environments, scholarly research investigations into the person-environment fit in the context of older adults have gathered considerable attention across developed nations (Salmistu & Kotval, 2023). The advantages of creating age-friendly neighbourhoods have been extensively studied and presented in research from developed nations; research on relationships between built environment aspects and active and successful ageing has been in the infant stage in India.

IMPORTANCE OF AGE-FRIENDLY CITIES

Various scholars link outdoor environments' quality and accessibility with opportunities for enhancing inclusiveness and quality of life among older adults. As a minimum of 150 minutes per week of physical activity (PA) is recommneded to maintaining healthy ageing, neighbourhoods with green open spaces in close and walkable vicinity encourage ageing individuals to enhance opportunities for physical activity. Low-quality outdoor spaces create physical barriers andggravate psychological challenges towards carrying outdoor basic ADLs (Liu *et al.*, 2023). When living arrangements are limited as older adult couples or alone, any physical or psychological ailments exacerbate feelings of isolation and increased risk of fear of tripping or falling while performing physical activity necessitating active mobility between home and outdoor environments. As such, several outdoor public and green open spaces such as parks, playgrounds, lawns, and community, religious and retail centres become the first choice of older adults.

Public Open Space Availability

Researchers from the social science and medicine field stress the need for the availability of public green open spaces within neighbourhoods for positive effects on self-perceived perceptions of health and well-being among the most vulnerable demographic groups, particularly older adults. Not only do these Urban green spaces (UGS) create opportunities for carrying out physical activity, but they are often considered to have positive effects on the psychological health of older adults. The correlations between opportunities for active ageing and the quality of outdoor neighbourhood spaces, as well as how such open spaces function in the contemporary times of changing urban planning priorities in the face of urbanization pressures characterized by shrinkage of available open spaces for development are few crucial aspects that may be necessary for planning bodies to comprehend (Lee *et al.*, 2015).

Active Ageing and Outdoor Accessibility and Mobility

Many scholars from the Western developed nations have discussed the safety and comfort of accessibility and mobility. While outdoor safety perceptions are often linked to traffic conditions, pedestrian conditions and availability of amenities, the willingness of older adults to traverse through the outdoors is also dependent upon the aspects related to design, maintenance and absence of physical barriers to walkability(Mercader-Moyano *et al.*, 2020). Associations between physical activity levels, destination and route characteristics, along with neighbourhood characteristics have been studied by scholars in the past (Zhang *et al.*, 2024). Researchers relate varied outdoor activities requiring outdoor mobility in the category of physical activity (PA) for leisure, shopping and exercise.

Traditional Neighbourhoods and Ageing-in-place

Most traditional neighbourhoods that attract tourists with their exceptional built environments also offer excellent outdoor places for older adult citizens, who typically have a long-standing physical and psychological association with these cities. Not only is the environment a significant aspect, but neighbourhood and city environments are also capable of fostering community connections and the inclusion of older adult populations. Perspectives of planning building contemporary neighbourhoods and city planning perspective align with the ideas of traditional city planning principles, which centre on the design of compact neighbourhoods characterized by a land use mix and well-connected vehicular and pedestrian accessibility (Meetiyagoda, 2018). Providing such a built environment becomes advantageous to older adults as it offers access to places for acquiring basic needs, activities, and commodities in a comfortable and safe walkable environment. Lifestyle variations and social connectivity needs vary a lot among the younger generations, and shifting to newer places often affects the mental health and outdoor activity patterns among older adults, leading to social isolation. Researchers have exhibited the effects of uncontrolled and unplanned development resulting in the decay of these central heritage districts in most towns. Under the stresses of overcrowding and tourism expansion, the social and spatial needs of these neighbourhoods' original and long-term inhabitants, particularly older adult residents, are compromised (Yung *et al.*, 2016). Researchers opined that planning the neighbourhood and city environments can benefit a larger populace by providing an optimal built environment that caters to the interests and needs of the entire community, enhancing the capacities for independent functioning capabilities and alleviating the stresses on care providers.

While research on linking ageing-in-place and active ageing with person-environment fit has garnered much attention in developed nations, comparable studies are still in their infancy state in the case of developing countries like India. Therefore, the article aims to understand the physical and psychological challenges from the neighbourhood outdoor built environments towards independent and active ageing in Indian urban areas.

METHOD

The study hypothesized that the quality of neighbourhood public and green open spaces, along with the accessibility to such outdoor spaces, strongly impact the overall satisfaction level of older adults. Survey data was collected to gain insights into the perception of older adult residents in Jaipur City, India. The study was conducted in 2022 during morning and evening hours. A structured questionnaire was administered to older adult residents of Jaipur to reflect their perceptions about the suitability, quality, and availability of outdoor public and green open spaces within their neighbourhoods and surrounding areas. Two variables, public green open space quality (NPGOS) and accessibility conditions (AC), were considered independent for inclusion in the survey instrument. Likert scale was used to assess the responses of older adults. Outdoor satisfaction level (OSL) was assumed as a dependent variable. The survey items were finalized through secondary literature review, focus group discussions and experts from academic and professional backgrounds. Since a lot of older adults exhibited unwillingness to talk to strangers and go outside for the recommended time of PA to the parks and other public areas in the wake of the psychological barriers caused by the outbreak of COVID 19 pandemic in India, random sampling was conducted to gain survey responses from the 60 years and higher age groups. Furthermore, administering online questionnaires was not preferred to reach the older adult residents in Jaipur, who are uninformed about email and other online communication tools and social media, and thus the aforementioned reasons attributed to the fewer survey responses limited to 70 respondents.

Along with the descriptive analysis of the characteristics of the sample population, regression analysis was performed on the survey responses using the IBM SPSS Statistics 20 package. Data collection was conducted in an urban region under the municipal jurisdiction of Jaipur city, as the research aimed to comprehend the traditional and modern lives of older adult people.

STUDY AREA PROFILE

Jaipur City, the capital of Rajasthan state, developed in 1727, is one of the few examples of a planned city in India. Also recognized as Pink City, the contemporary metropolitan city image originated from the walled city, the main heritage area of the city, from where the city expanded outwards to its present shape. Jaipur, having a total of 467 square kilometres of area, has a population of 3.1 million as per Census of India data. The walled city, also a major tourist destination of India, encompasses many famous and magnificent heritage structures and is enlisted as a world heritage site. Jaipur falls under the hot and semi-arid climate zone characterized by hot and long summers and mild winters and precipitation exceeding 625 mm annually. Jaipur offers several public and green open spaces at the city, local, and neighbourhood levels.

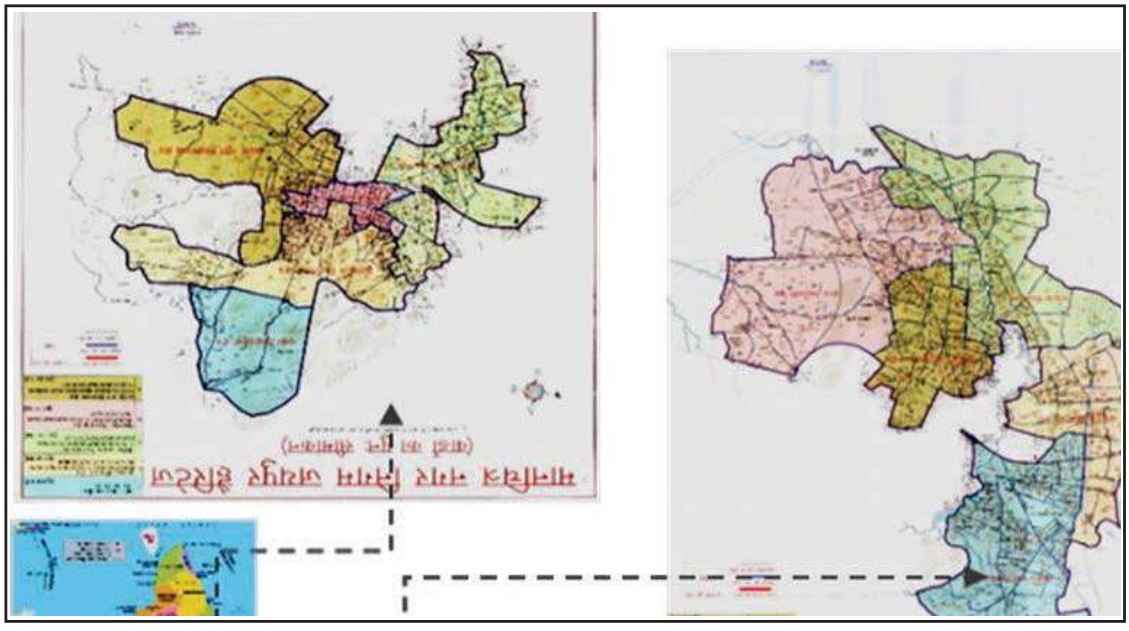

Fig. 1: Jaipur Location Plan. (***Source:*** Jaipur Development Authority)

RESULTS

Statistical analysis was carried out on the data derived from the survey responses. Descriptive analysis helped to understand the critical characteristics of the sample population. Ass seen in Figure 1, out of 70 respondents aged 60 years and above who participated in the survey, 41 were male while 29 were females (Fig. 2). The Number of females was found to be generally low in most open spaces for engaging in daily outdoor activities like walking or exercise and preferred to remain engaged in their domestic daily activities. Almost 67% of older adults live in a joint family structure, while 30% of them stay as couples.

Data also exhibits that while most older adults go outdoors for daily physical activities at least once a day, there was a visible decline in levels of out-of-home engagements as age declines among older adults.

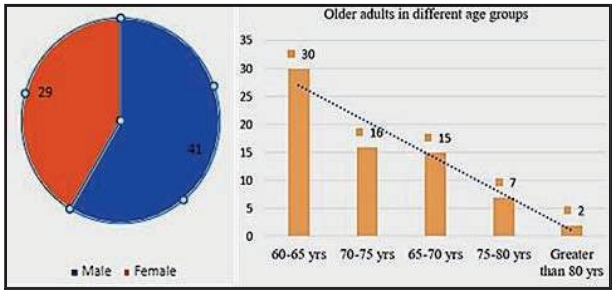

Fig. 2: Sample Population's Composition

Almost 58% of adults exhibit carrying out physical activity daily, and 21% of them showcased never or rarely carrying out any outdoor physical activities, which was either due to walking-related or other health ailments. Also, some older adults perceived the fear of falling and tripping and strenuous walking environments as psychological barriers.

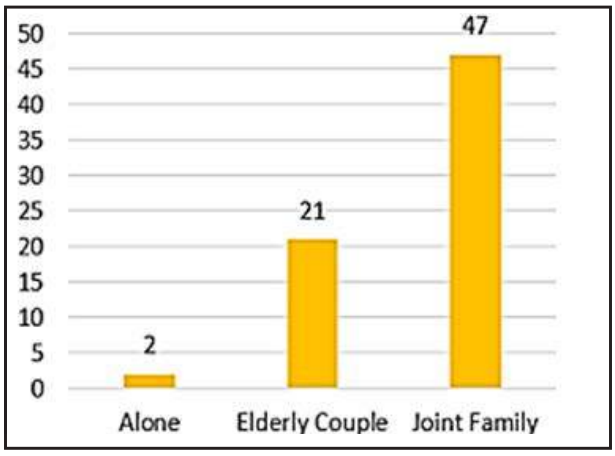

Fig. 3: Living Arrangements Among Respondents

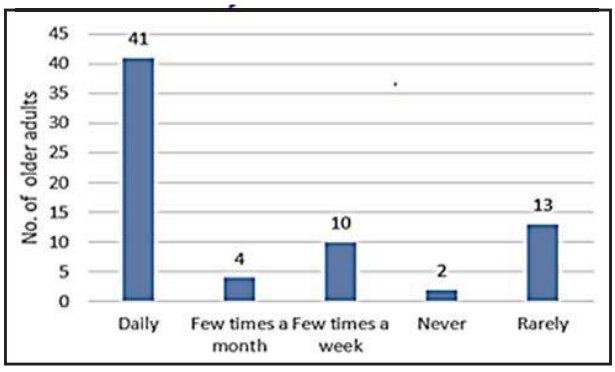

Fig. 4: Frequency of Outdoor Activity

Association Between Neighbourhood Public and Green Open Spaces

About 64% of older adults agree that public green open spaces are located in walkable proximity to their home environments. While 41.4% were unsatisfied, 38.6% of older adults feel satisfied with the maintenance and cleanliness of public and green open spaces. The percentage of older adults satisfied (54.3%) with the availability and adequacy of micro amenities like seatings, provision of litter bins and rain shelters was higher than those unsatisfied (17%) with it, while almost 40 % had neutral responses. Almost 48% of older adults showcased satisfaction with the provision of artificial lighting. A higher percentage of the population exhibited concerns about the availability of clean drinking water and toilet facilities. Almost 34% of older adults exhibited concerns about the lack of universal accessibility at easy entry and exit points to such places. Similarly, a higher percentage of older adults were satisfied with the adequate shading and safety in the public green open spaces.

Accessibility Conditions

A relatively higher number of older adults (58%) showcased dissatisfaction about their safety due to higher traffic speeds of bikers on internal streets and provisions of controlling the traffic speeds through traffic calming measures. More than 55% of older adults considered their experience of crossing roads as threatening and uncomfortable. While 44% of older adults were dissatisfied with the provision of pedestrian user traffic signals and signages, almost 26% were unaware of such measures. 44% of the respondents were satisfied with the maintenance and quality of sidewalks and pedestrian walks, while 32% exhibited discontentment. 33% of respondents did not consider the sidewalks to be obstructed by parked vehicles or vendors, while a higher percentage of the population exhibited concerns about the presence of street furniture on their usual routes for outdoor activities.

Inferential Statistics

Inferential statistical analysis was performed using the IBM SPSS 20 statistical package along with the descriptive analysis. Correlation analysis was performed between OSL, NPGOS, and TC variables. There was a higher correlation between AC and OSL at .629 and a significance level of .000. Also, the NPGOS had a positive influence on OSL at .619 at a significance level of .000. Correlation between all three variables was found to be significant at 0.01 level representing a positive strong correlation between the variables.

Table 1: Correlation Matrix

		OSL	IPGOS	AC
OSL	Pearson Correction	1	.619**	.629**
	Sig. (2-trailed)		.000	.000
	N	70	70	70
NPGOS	Pearson Correction	.619**	1	.638**
	Sig. (2-trailed)	.000	–	.000
	N	70	70	70
AC	Pearson Correction	.629**	.638**	1
	Sig. (2-trailed)	.000	.000	–
	N	70	70	70
** Correlation is significant at the 0.01 level (2-tailed).				

Regression Analysis

Regression analysis was performed to determine the causal effects of neighbourhood public and green open spaces

(NPGOS) and accessibility conditions (AC) on overall satisfaction levels (OSL) among older adult residents. Results (Table 3-6) indicate a strong causal effect of neighbourhood public and green open spaces on the overall satisfaction levels OSL). The impact of accessibility conditions (AC) on the overall satisfaction level of older adult residents residing in Jaipur city has been identified as relatively more significant, with a t-value of 3.427 and a significance level of .001. NPGOS, having a t-value of 3.191 and a significance level of 0.002, is also a significant impactor for OSL. ANOVA was performed on the survey responses data, which reflected the model to be significant as indicated by the F-statistics (f=30.290, p<0.01). While both the predictor variables have a strong influence on OSL, accessibility conditions (AC) have a relatively higher influence on the OSL.

Table 2: R square values statistics

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.689[a]	.475	.459	.57940

Table 3: Cofficients for Regression model

Coeffucuebts

Model		Unstandardized Coefficients		Standardized Coefficients	t	sig.
		B	Std. Error	Beta		
1	(Constant)	1.245	.284		4.392	.000
	NPGOS	.350	.110	.367	3.191	.002
	AC	.372	.109	.394	3.427	.001

a. Dependent Variable: OSL

(***Source:*** Author)

Table 4: Residuals statistics

	Minimum	Maximum	Mean	Std. Deviation	N
Predicted Value	2.2678	4.6375	3.3607	.54290	70
Residual	-1.41775	1.13741	.00000	.57094	70
Std. Predicted Value	-2.013	2.352	.000	1.000	70
Std. Residual	-2.447	1.963	.000	.985	70

a. Dependent Variable: OSL

(***Source:*** Author)

Table 5: ANOVA statistics for model

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	20.337	2	10.169	30.290	.000[b]
	Residual	22.492	67	.336		
	Total	42.829	69			

a. Dependent Variable: OSL b. Predictors : (Constant), NPGOS

(***Source:*** Author)

Observational Analysis

Results from the regression indicate that there is strong evidence in support of the study hypothesis, as the independent variables (NPGOS and AC) have a substantial impact on the overall satisfaction level. Along with the reported reponses from older adults, several issues were also observed by the author which affirmed the reponses of lower satisfaction for the traffic and accessibility conditions. Older adult residents reported good satisfaction with the planned public and green spaces in Jaipur city. Visiting religious buildings like temples was also considered a daily outdoor activity and an opportunity for many older adults to engage in social interactions. Most of the religious buildings, bazaars, and other places of daily outdoor activity had visitability issues in the heritage areas of the city in the absence of lifts and ramps for access for older adults using some walking aids. While the reported satisfaction levels for the availability of green open spaces were considerably higher, amenities like the provision of clean filtered water and age and disabled-friendly toilets with in the public and green open spaces were observed to be lacking. Hygiene is such facilities was also a matter for concern.In absence of any signage, sasily locating such facilities was also as a concern, along with the maintenance of such facilities, which was reported as unsatisfactory by most older adults. While the overall satisfaction from the availability and quality of green open spaces along with the amenities provided within such spaces was found to be satisfactory, accessibility and walkability challenges were a matter of concern among majority of older adults. Although the proximity of the public and green open spaces to one's home environment was not considered a matter of concern, strenuous traffic conditions were regarded as a barrier to the comfortable walking experience by older adult residents. Two wheelers were seen to be driving in wrong direction at threatening speeds for older adults. Road crossings in different parts of cities lacked the provision of pedestrian user traffic signal systems. The absence of median islands on the roads and traffic-calming devices was observed to cause psychological and physical barriers to the walking experience through the neighbourhoods. Moreover, zebra crossings were generally obstructed by the vehicles and older adults were seen to be crossing busy roads at unsafe spots. Pedestrians and sidewalks were also obstructed by parked vehicles, and sidewalks lacked artificial lighting in a few spots. Buffers to safeguard pedestrian users from traffic were also not present along the busy roads, and bikers were seen driving recklessly on the pedestrian sidewalks. Maintenance concerns were also seen as a matter of concern for smooth walking experiences in the outdoors. Pedestrian connectivity lacks various amenities like resting places, provision of benches, natural or artificial shading, clean and adequate potable water facilities, and washrooms at different locations; most older adults showcased a lower inclination towards carrying out the usual activities like walking and exercising.

DISCUSSION

The survey data and statistical analysis exhibit robust evidence supporting the notion that the perceived satisfaction levels of older adults are significantly influenced by the availability and quality of public and green open spaces (NPGOS) along with the accessibility conditions (AC), as postulated by various researchers in their studies (Dallat *et al.*, 2014; de Vries *et al.*, 2013; Yang *et al.*, 2021). A higher correlation indicates neighbourhood public green open spaces to have a strong influence on the overall satisfaction levels among older adults. The data can also be understood to underscore the influence of ease of accessibility and walkability conditions on the linkages between the home environment to the neighbourhood public and green open spaces. Urban policies have focused on developing wider roads to increase the infrastructure demands for an increasing number of vehicles in cities, but in the absence of pedestrian safety provisions on such road networks, such pedestrian infrastructures become inaccessible to pedestrian users, particularly older adults and persons with disabilities. Walkability enhancements within and around the neighbourhood environments can have the benefit of offering opportunities for leisure activity and socializing, but it also provides an indisputable benefit of bolstering their psychological positivity to be functionally independent. (Kim *et al.*, 2024). The study aligns with the findings of numerous researchers that emphasize the benefits of planning age-friendly public and green open spaces in the compact environment of the neighbourhoods as the means to promote social inclusion among older adults(Kim *et al.*, 2024). Our study highlights the need for enhancing safety for independent moblity. Such threats are largely evident in heritage neighbourhoods, where traffic vlumes remain high and mostly uncontrolled. In line to the findings of Yung *et al.*, (2016) , our study highlights the benefits for providing pedestrian amenities along the pedestrian networks improves the walking experience amog older adults. Benefits of planning green open spaces in home proximity is associated with opportunities of social connectedness thus improving mental health of older adults and thus our study thus aligning with Del Aguila, (2021).

Additionally, the study supports the notion that despite the quality of public open space, obstacles to active mobility, such as hazardous and uncontrolled traffic conditions and unfavourable pedestrian conditions, pose a significant psychological challenge for older adults who wish to engage in outdoor activities (Rehal *et al.*, 2024).

CONCLUSION

The study seekss to elucidate the correlation between the availability of neighbourhood level green open space and the ability to engage in outdoor physical activity. The findings of the public opinion surveys reveal that most of the outdoor engagement in the green open spces among the older adults are predominantly influenced by the accessibility conditions. The pedestrian networks quality between home and outdoor green open spaces are the most important facility that have the potential to ecourage or impede daily outdoor phsical activity. Poorly planned pedestrian amenties often deteriorates the independent walking experiences. Poorly developed road crossings are the biggest threat for older adults both in the walled city and the contemporary city. Furthermore, when green open spaces are located in the home proximity without necessitating traffic crossings, the outdoor activity experience becomes exceptionally comfortable and conducive to most older adults..

When independent mobility abilities decline, a support from the family members is important asset for assisted walking to the green open spaces and as such the joint family becomes a crucial support for daily engagements. The role of urban design and universal design thus becomes crucial for designing age-friendly urban green open spaces and their linkage routes. The study makes a crucial contribution to measure the role of green open space avialabiltiy and acccessibility conditions in urban areas of Jaipur city, India. Further, the study despite the study

Despite a smaller sample size, attributed to pscycholical contraints exibited by older adults, the study serves as a significant resource for urging planners and designers to plan age-friendly green open spaces and create pedestrian-friendly outdoor conditions in unban built environments in India, thereby fostering equitableopportunities for social engagement and physical activity among older adults incuding differently abled persons.

The authors endeavour to test the generalisability of the study in a multiple-city survey approach as a prospective direction of research.

CONFLICT OF INTEREST

No conflict of interest was declared by the author

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Does the Physical Environment of an Urban Neighborhood Affect the Social Well-Being of Children? A Pilot Study in Nagpur, India

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Abstract—
Purpose: This paper investigates the influence of urban neighbourhood environments on the social well-being of Indian children, focusing on the social development domains. It seeks to understand the relationship between children's social connectedness **(SC)** and the outdoor physical environment **(OPE)** during middle childhood. **Methodology:** The conceptual framework of this pilot study was based on Bronfenbrenner's Person-Proximal Process-Context model of human development. The proximal process was operationalized as children's outdoor out-of-school physical activities **(OOPA)** as a means of interaction with the physical and social environment. Adopting the cross-sectional quantitative method approach investigation was conducted in three neighborhoods. The study included subjective measures collected through in-person surveys (N=70) of 8–12-year-old children and objective measures computed using GIS. A strong correlation was found between children's daily duration of OOPA and SC, validating the PPC model's proposition of proximal process. SC and its linked dimensions show the significant influence of objective variables like building density, street connectivity, traffic exposure, quality of recreation spaces in the neighbourhood and subjective perceptions like personal safety and neighbourhood physical activity environment. Children's gender, motivation for outdoor physical activities and license for independent mobility were also found to influence social connectedness. The study confirms that OOPA is the profound connector between the OPE and their social development as it facilitates children's interaction with the outdoor physical and social environment. Children's SC and its linked dimensions were directly associated with objective OPE and perceived characteristics of the neighbourhood. The study also shows a significant association between active and independent mobility and children's SC. Considering well-researched evidence of linkages between the built environment and children's active and independent mobility, this study suggests the additional indirect influence of OPE on children's SC through their travel behaviors.

Keywords: Middle childhood, Urban Neighbourhoods, Social Development, Social connectedness, Outdoor Physical Activities.

INTRODUCTION

Children of Urban India

In the last couple of decades in India, the combined forces of urbanisation, liberalisation, and globalisation along with the spread of dominant cultures and impingement of ICT in people's everyday lives have resulted in accelerated transformations in physical, sociocultural and economic

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domains of the urban population (Saith & Wazir, 2010) including its large population of urban children (35.9% share) (Census, 2011; Kundu, 2020) Alongside, in the wake of the demographic dividend and its promise for the young population to become a major contributor to the country's present and future economic growth as human capital, India's children become major stakeholders in the urban agenda. ((Harjani, CNBC, 2012, Oct 24). - Google Search, n.d.) Challenges, particularly related to the transforming urban environments and children's social well-being are highlighted here. (i) Uncontrolled urbanization led to undesirable physical transformations like a congested and near breakdown of services in the urban core, car-dependent and infrastructure-deficient fast-expanding urban fringes, diminishing open spaces and parks and playgrounds, vehicular dominance on urban streets; increased travel time to school, new housing typologies imposed on the conventional residential environments (Pedram *et al.*, 2024) are not only creating challenges for children to utilise outdoor spaces but also affecting the local social circumstances for them. (ii) The ingress of ITC technology in children's play and communication patterns, and commodification of play, are some of the interrelated processes that manifest themselves in the daily lives of children in the form of changes like sedentary lifestyle, increasing virtual communication patterns (Pedram *et al.*, 2024) diminishing social interaction and integration. (iii) Other changes influencing children's immediate social environment are changing parenting styles influenced by overprotectiveness and time shortage syndrome (Rudd, 2019) placing restrictions on children's independent exploration of outdoor environments and socialization (Pedram *et al.*, 2024).

How are Our Children Doing?

The cumulative effect of the above-mentioned urban transformations poses complex challenges for children's physical and mental health and social lives. Some alarming recent trends in children's physical and mental health are discussed herein. Worldwide, up to 10–20% of children are affected by mental health problems (Kieling *et al.*, 2011) and as per WHO reports, self-harm and suicides are the most common causes of mortality after road accidents among the young population. In India also estimated suicide rates are as high as 35.5 per 100,000 population among young people which is the highest in south-east Asia (WHO, 2017). Global School-Based Student Health Surveys (GSHS, 2007) have highlighted the prevalence of mental health indicators like depression (25%), distraction (11%), anxiety (8%), loneliness (8%) and having no close friends (10%) among Indian children (WHO, 2017). There are up to 20 million adolescents with a severe mental health disorder, which is a growing concern (Shastri, 2009). The NCD's contribution to the total disease burden in India rose to 61.8% in 2016, a concerning trend linked to the rise in levels of urbanization across Indian states as evidenced by current studies highlighting the growing prevalence of obesity, T2 diabetes and psychological distress among the Indian young population in recent years (ICMR & PHFI, 2017; Mehreen *et al.*, 2020; Ramadass *et al.*, 2017; Saikia *et al.*, 2016).

New Emerging Needs

Several positive health approaches for children recommend community connectedness and several related social aspects like social relationships, social acceptance, social coherence and integration as protective factors for mental health and an essential component of healthy development and quality of life (Cummins & Lau, 2005; Keyes, 2002; W.H.O, 1996). Apart from being a priority as a future human capital, action is imperative to inform public health interventions to address mental health issues and create a liveable environment for children's healthy development. It implies that India's urban environments (Tiere-I and Tier-II cities) will play an influential role in fostering the health, development and well-being of the country's growing young population.

Beyond Prevention, a Developmental Approach to Child Well-being

International forums like UNCRC, upholding children's equal rights to development, protection, and participation have been instrumental in expanding the traditional poverty & survival-centric approaches to wider multi-dimensional approaches to include both material and non-material aspects of **child well-being (CWB)** (Camfield *et al.*, 2010; Saith & Wazir, 2010). Article 27 of CRC calls for a standard of living adequate for the child's physical, mental, spiritual, moral and social development' (Bartlett, 2002). India being a ratifying country for UNCRC, needs to take up a wider and holistic framework for CWB and development. Healthy child development involves mutually related aspects like physical, mental, psychological and social health and health-promoting behaviour, and to understand it holistically it needs to be contextualised (Bartlett, 2002; Ben-Arieh *et al.*, 2014; Pollard & Lee, 2003).

Convergence of Child Development and Urban Environment

Theory and research have recognised the neighbourhood, where children live and grow as an important ecological context (Physical and social environment factors) for understanding CWB and development (Bronfenbrenner, 1979; Leventhal & Brooks-Gunn, 2000). Previous studies have investigated the effect of a neighbourhood's structural/ compositional factors (income, employment, racial composition) and social /organizational factors (disorder, safety, social cohesion) on children's developmental outcomes but the influence of fundamental facets like physical, & natural environment on child development is largely ignored (Leventhal & Dupéré, 2019; Vaden-Kiernan *et al.*, 2010). The persistent epidemic of obesity and mental health issues among children in high-income countries has encouraged health research to extend from a person-centred approach to broader everyday environments to investigate factors influencing children's active living (Woolcock & Gleeson, 2007). Consistent with this trend extensive research has explored the relationship between the neighbourhood's PE and children's PA and health (Davison & Lawson, 2006). Yet the potential effect of neighbourhood PE on children's other domains of development particularly social well-being has been largely under-studied internationally and in India (Bhonsle & Adane, 2015; Khatavkar, 2018). Although extensively studied in developed countries, the research on exploring the neighbourhood BE effects on children's health and well-being is nascent in India. A few studies from India have investigated this association of urban BE with some aspects of children's health and well-being such as PA, (Bhonsle & Adane, 2015; Chatterjee, 2006; ICMR & PHFI, 2017; Khatavkar, 2018) independent mobility (Tyagi & Raheja, 2021) and active travel to school (Cooper *et al.*, 2006; Eccles, 1999). There is a near absence of studies exploring the relationship between neighbourhood PE and children's other key developmental domains in India (Tyagi & Raheja, 2021).

Bridging the Gap: Research Goals and Objectives

India's urban areas are expected to continue as growth poles with a 600 million urban population and 75% share of GDP by 2030 (PwC India & Save the Children India (2015)). Alongside an absolute number of urban children, a limited-time window of demographic dividend (2005-6 to 2055-56), an evolving landscape of child development in urban India and the ambitious goals of the New Urban Agenda, set to be achieved shortly present a crucial intersection that demands intensive investigation. Overwhelming urban expansion and large population of urban children along with India's unique other challenges like, financial constraints, and diverse socio-economic and cultural character, large-scale individual interventions for child development may prove impractical. Instead, it may be useful to take up a public health approach with a focus on the relationship between the physical environment and child development and investigate the linkages and implications to ensure that urban development in India may truly serve the best interests of its youngest citizens.

Addressing this research gap, this study aims to explore the association of the outdoor physical environment (OPE) with social development, measured as the social connectedness (SC) of children during middle childhood (8-12 years), at the neighbourhood scale in the city of Nagpur in India. This study is a part of an ongoing larger study focused on investigating the association between neighbourhood PE and key developmental aspects of middle childhood.

Obj-1: To identify the difference in children's social connectedness across the three neighbourhoods and gender.

Obj-2: To investigate the association between children's social connectedness and OPE characteristics of the neighbourhood.

Obj-3: To get preliminary insight into the potential pathways through which OPE characteristics and other related factors influence SD during middle childhood.

This literature review explored the multifaceted relationship between child development and the physical urban environment specifically focusing on social development and social well-being during the middle childhood development stage and on the outdoor physical environment of the urban neighbourhood. The literature was reviewed to address specific research questions such as, How does child development contribute to children's well-being?; What are the developmental goals during middle childhood?; What are the key activities, interactions and resources through which the outdoor physical environment might influence the social development of social connectedness during middle childhood?; What are the appropriate theoretical frameworks to study the relationship of outdoor PE with the social development and well-being of children? A systematic search of relevant scholarly literature was conducted utilizing prominent databases such as Google Scholar, ResearchGate, PubMed, CINAHL Plus, and PsycINFO. Key search terms included domains of child development,

middle childhood development, social connectedness and wellbeing, urban and neighbourhood environment, and outdoor physical environment, Peer friendships, physical activities. The literature referred to included peer-reviewed articles, dissertations, and reports published in the last decade that investigate the impact of the built environment on children's physical and social development, particularly during middle childhood (ages 8-12).

Development During Middle Childhood

Childhood development is a continuous process of transformations across physical, cognitive, emotional, and social, dimensions but children develop in specific domains during specific development stages, provided they get requisite environmental stimuli and opportunities (Cherry, 2023). ***Middle childhood (MCD)*** (6-12 years) is also a distinct development stage with a particular set of tasks and needs (Cooper *et al.*, 2006; Eccles, 1999). During this stage, children undergo important changes in the developmental domains which manifest in the form of personality traits, behaviour patterns and incipient competencies which even affect development in adolescence and adulthood (DelGiudice, 2018; Moore & Theokas, 2008; Schonert-Reichl, 2011). During MCD, there is the intrinsic bio-psychological drive to achieve competency, independence and relatedness, due to which children naturally seek opportunities for acquiring and exhibiting new skills, assert their choices, even learn to control their behaviour and want to form relationships with peers and other adults (Eccles, 1999; Schonert-Reichl *et al.*, 2013). The decision to focus on MCD for this investigation is supported by several studies studying neighbourhood effects on children's several social development (SD) outcomes like peer friendships, (Rogers, 2012) place attachment, **physical activities (PA) and active travel (AT)** (Kyttä *et al.*, 2012). National studies of the same genre have also focused on the same age group and have investigated children's **independent mobility (IM)** (Tyagi & Raheja, 2021) travel to school (Tetali *et al.*, 2016) daily activities, and play provisions (Bhonsle & Adane, 2016).

Friendships and Social Development During Middle Childhood

SD refers to the acquisition of personal and social skills, attitudes and behaviour that enable an individual to function in society and it is called socialization. (Seefeldt, 1986), At the onset of MCD, when children begin venturing outside into the physical and social environment, peers, play, and **physical activities (PA)** become powerful agents of their socialization leading to SD. During MCD, friendships take a prominent role and peer interactions become instrumental in fostering companionship, a sense of belonging and motivation for participation in social activities. (Morrow, 2001) Organized sports, informal play, team games and active travel all have different dimensions of social experience. (Sage, 1986, p.346 as cited in Seefeldt, 1986) Outdoor play, exploration, and co-occurring social interactions nurture cognitive abilities that promote communication skills and greater social awareness and facilitate more complex interactions. Hartup, (1996) provides a frame of dimensions to understand the developmental significance of friendships. (i) Having friends: It's an indicator of being socially liked and is a developmental predictor. Children who have friends are more socially competent, less troubled, sociable, and cooperative. (ii) Friendship Quality: High-quality friendship is characterized by prosocial behaviour, intimacy, social adjustment, and the ability to cope with stress and affects other aspects of SD. (Berndt & Keefe, 1995)

Concludingly, good friendships (both quantity and quality) provide benefits such as companionship, sociability, feelings of self-worth, emotional security, affection, and well-being (Berndt, 2004) and lack of friendship is associated with conflicts, low self-esteem, and confidence, social withdrawal, poor self-regulation and impulsive risk-taking behaviour. (Mitic *et al.,* 2021) Developing, maintaining and being functional in a stable group, and interacting with peers and members outside the family is a crucial SD task during MCD. (Berndt, 2002, 2004)

Research Insights into the Neighbourhood and Children's Social Development

Research exploring PE effects on a child's development has majorly focused on physical health, PA, obesity and mental health. (Biddle *et al.*, 2004; Transportation Research Board & Institute of Medicine, 2005) However, some evidence suggests that neighbourhood provide important exposure, resources and opportunities to explore the surroundings, learn and interact with people. (Hazen, 1982) MCD is a period when children often in collaboration with their friends, 'colonize' and extensively explore the outdoors. (Hartup, 1996; Moore & Theokas, 2008) Certain neighbourhood OPE characteristics have been identified as supportive of children's use and exploration. Walkable neighbourhood, characterized as having higher density, land-use mix, connected street networks, and highly accessible destinations have been associated with increased social

interactions, as people are more likely to walk, cycle, and linger locally (Goldfeld *et al.,* 2015). Unsafe neighbourhood may force children to be isolated in their homes, restricting their opportunities for peer play and social interactions (Morris & Kalil, 2006, p.237). Neighbourhood recreation facilities, and other utility destinations like libraries, schools, and hobby centers provide opportunities for social interactions, forming relationships and fostering meaningful social connectedness (Jago *et al.,* 2009). Although there is indicative research evidence and a theoretical platform for expecting neighbourhood PE to influence children's SD, there is a lack of studies examining this relationship (Villanueva *et al.*, 2016).

Theoretical Perspectives

Ecological frameworks are often employed in to examine the neighbourhood PE influence on children's physical and mental health and health behaviour in urban planning disciplines (Giles-Corti *et al.,* 2005). Bronfenbrenner in his bioecological model, puts relationships in the context of ecological systems and stipulates the environmental context as a powerful determinant of human development. The reciprocal interactions between different systems connected via social interactions are considered effective processes through which human development is brought about (Bronfenbrenner & Morris, 2006; Mitic *et al.*, 2021). Sampson *et al.,* (2002) has also outlined four classes of neighbourhood mechanisms related to children's health and behaviour problems. (i) Social Ties/Interaction: Works through social relationships and builds social capital (Leventhal & Brooks-Gunn, 2000) (ii) Norms and collective efficacy: Operates through informal social control, and social cohesion (iii) Institutional resources: catering to the needs of the children (iv) Routine activities: The availability and access to everyday activities and places like schools, mixed land-use, recreation spaces, transportation options, activity vibrancy on the streets and at POS are relevant to understand patterns of children's social encounters with peers, adults, and their social activities (Sampson *et al.*, 2002). Considering the complex relationship between OPE and children's SD, an integrated framework that would consider the interconnectedness of social processes (peer friendships, social capital), resources and physical features (natural and BE features), spatial dynamics (diversity, variability and complex interaction within PE components) and individual differences (age, gender, income) would provide a suitable conceptual framework for the study (Leventhal & Dupéré, 2019).

METHOD

Conceptual Framework of the Study

The conceptual framework of the study is based on Bronfenbrenner's bioecological theory of human development. The essence of this theory is the 'Process-Person-Context'-Time' (PPCT for short) model which is particularly relevant for this study (See Figure 1) (Bronfenbrenner & Morris, 2006; Tudge, 2009; Xia *et al.*, 2020). The primary propositions of the PPCT model considered for the study are stated herein. (Ashiabi & O'Neal, 2015) (i) Human development takes place through the process of reciprocal interaction between an active, evolving biopsychological human organism and the persons, objects, and symbols in its immediate external environment. (ii) To be effective, interaction must occur regularly over extended periods. Such enduring forms of interaction in the immediate environment are referred to as proximal processes and these are the mechanisms through which developmental potentials are actualized (Bronfenbrenner, 1999; Högman *et al.*, 2020). (iii) The proximal processes are interpersonal interactions, as well as interaction with objects and symbols (Bronfenbrenner, 1999). (iv) Given the pilot study's limitations, (exploratory nature and cross-sectional data) a limited version of 'Process-Person-Context (PPC)' excluding the 'Time' component of the bioecological model was adopted in the conceptual framework (See Figure 1) (Ashiabi & O'Neal, 2015; Tudge *et al.,* 2009).

Constructs, Variables, and Measures

The operationalization of constructs, variables, and measures within the 'Process-Person-Context (PPC)' model as applied in the study is described below (see Figure1).

1) Social Development Outcome: Social Connectedness (SC):

The construct of (SC) is defined as an emergent property of SD and it assesses social networks and a sense of belonging and support from the neighbourhood peers and community (Moore & Theokas, 2008). Following the Middle Years Development Instrument (MDI, 2021 developed by HELP, UBC), (Schonert *et al.,* 2013; Thomson , 2018) the construct of social connectedness was operationalised as a composite variable including (a) Peer friendships: Measured as a count of the number of friends in the neighbourhood. (b) Quality of peer friendship: Measured with a five-item subscale of peer belonging and friendship intimacy covering aspects like kinship, sharing, and intimacy. The responses were

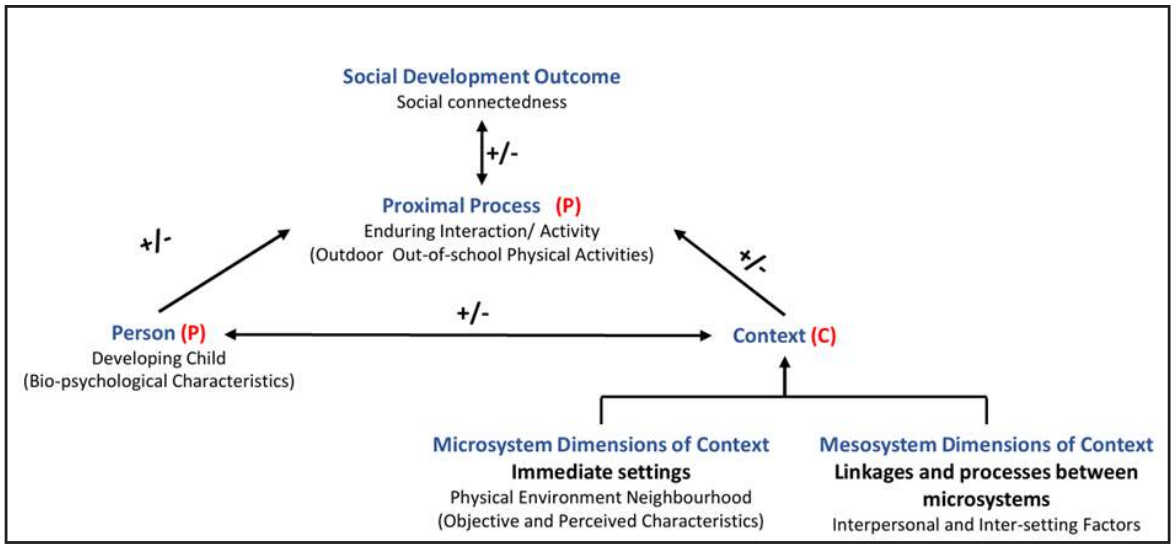

Fig. 1: Conceptual Framework to Identify variables
Reference: (Hayes et al., 2022; Schaerz, 2021)

scored with a 5-point Likert scale (Disagree a lot=5 and Agree a lot=1) (Berndt, 2002; Gadermann *et al.,* 2016; Thomson *et al.,* 2018) (c) Number of known adults in the neighbourhood: Measured as a count of number of known adults in the neighbourhood who are caring, helpful to children and important. (Islam, 2008) For the composite variable of SC a combined weighted score was also calculated for the correlation analysis.

2) The Proximal Process – Outdoor out-of-school physical activities (OOPA):

As mentioned earlier the proximal process of the (Process-Person-Context) model is operationalised as children's daily duration of OOPA in the neighbourhood. Out-of-school activities provide a venue for interacting and "networking" with other peers. (Ripke *et al.,* 2006) The spatial distribution of these daily activities in a way organises when and how children come in contact with neighbourhood peers and other community members. Regular OOPA promotes SC through their friendship experiences and greater social awareness. (Hagger & Chatzisarantis, 2005)

The OOPA was measured using three items adapted from existing PA questionnaires, Childre's Leisure Activities Study Survey (CLASS) (Huang *et al.*, 2009; Telford *et al.*, 2004) Other international and national PA study protocols were also referred to make the survey item suitable for local situations. (Health Behaviour in School-Aged Children (HBSC) Study Protocol, 2014; Mehreen *et al.*, 2020; Rosenberg *et al.,* 2009) Children reported categorical responses to items of frequency several days per week (Never/ Rarely; Once/2-3 days/ 4-5days, 6-7days) ((HBSC) Study Protocol, 2014) and duration in minutes over weekdays and weekends in a usual week. (<=30; up to 60; up to 90; up to 120 and >120) To obtain the overall estimate of the OOPA in a usual week the categorised time intervals over weekdays and weekends were first transformed into a continuous score per week and then the duration of OOPA per day in a week was calculated as adopted by the other studies. (Bringolf-Isler *et al.*, 2012)

3) The Context – Neighbourhood Outdoor Physical Environment (OPE)

Focusing on the neighbourhood OPE as a microsystem dimension of the context (See Fig 1), as postulated in the 'Process-Person-Context (PPC)' model, we further anchor on relevant pathways of neighbourhood influence on child development as outlined by Sampson, (i) Physical characteristics (ii) Resources, (iii) Disorder and safety (children's perceptions) (iv) Children's routine activities. (Sampson *et al.,* 2002) Further tapping the operational research frameworks from health-promoting and child-friendly environment research like, 'Ecological models of PA determinants' (Bauman *et al.,* 2012) and 'Ecological model of active living' (Sallis *et al.,* 2006). to identify relevant features of OPE that influence child development. Considering the many overlaps among these frameworks we adopt an integrated approach to identify OPE attributes

that comprehensively capture the objective and perceived characteristics of OPE that may influence children's OOPA, which is hypothesised as the interface between OPE and the socially developing child. Referencing to the previous discussion presented in the literature section of this paper, we have identified six OPE attributes along with ten objective and three perceived OPE variables as described in (Table 2).

Assuming that ease of movement in the neighbourhood unfolds opportunities for social activities along with physical exploration, mode of travel to school (Inter-setting) and licence for independent mobility (Interpersonal) are the two mesosystem dimensions of the context included in the framework. (See Fig 1) (Babb *et al.,* 2011; Högman *et al.,* 2020; Loebach & Gilliland, 2022; Tetali *et al.,* 2016)

4) The Person: Gender

The 'Person' in the Process-Person-Context' model (Bronfenbrenner & Ceci, 1994) is postulated as personal characteristics (biopsychological) that either initiate or inhibit the proximal process of interaction. (Högman *et al.*, 2020) The study includes variables of (i) Gender (biological) and (ii) Motivation for PA as personal characteristics of the child, which is hypothesised to influence children's PA and SC. (Biddle & Mutrie, 2001; Frank *et al.*, 2005)

5) Socio-demographic Factors

Age and Monthly household income are the two variables that were included in the study as demographic information to ensure the recruitment of children within the target age range (8-12 years) and socio-economic category (MIG-I & II). (Davison & Lawson, 2006; Ding *et al.*, 2011)

Study Settings

This study was conducted in Nagpur, the second capital of Maharashtra has 24.48 lakhs population (Census, 2011). It's central India's regional centre for commerce, industries, services, health and education. In the last two decades, there have been progressive changes in Nagpur's industrial, and economic profile leading to real estate growth especially induced by the MIHAN project (Comprehensive Mobility Plan for Nagpu - Google Search, n.d.). Coupled with significant in-migration is transforming the city physically, socially, and culturally. Rapid changes in the urban landscape are putting the city's infrastructure under stress resulting in urban sprawl, increased densities, higher crime rates, increase in traffic volume, and lack/ shortage of open spaces, leisure and amenities are affecting liveability for children. Nagpur, a tier-II city is significant as a representative case of transforming the urban living environment in India, hence a suitable context for exploring the relationship between OPE characteristics and child social development.

Neighbourhood Selection

A multiple case study approach was adopted as the study focused on examining the real-life context. As discussed before, OOPA is hypothesised as an interface between OPE and the socially developing child assumed to enhance children's opportunities for regular social interactions and experiences. We identified four OPE factors (proportions of intersection & commercial use streets, heavy traffic roads, and amount of recreation open spaces) known to support children's daily duration of OOPA, forming the selection criteria for identifying the study neighbourhoods. (Biddle & Mutrie, 2001; Frank *et al.*, 2005) Three neighbourhoods from Nagpur namely, Trimurti Nagar (TN), Jaripatka (JP) and Besa (BS) were carefully selected based on the preliminary cluster analysis of four OPE factors (selection criteria) and were computed using GIS within tentatively delineated neighbourhood boundaries by direct site observation and consultation with the neighbourhood residents. The purposeful selection of three neighbourhoods was aimed to maximise variability in the level of PE supportiveness (high, medium and low) for OOPA and social interactions within the pilot study. (See Table 1)

DATA COLLECTION

Subjective data

The cross-sectional data for this pilot study was collected from the interviewer-administered survey of children (N=70) 8-12 years old belonging to middle-income households recruited from three neighbourhoods covering the whole spatial range. There were several reasons behind using this method for collecting subjective data on perceptions, certain PE characteristics and outcome variables like social connectedness as discussed here. (i) Limited awareness about the usefulness of academic surveys (ii) Parental apprehension regarding interacting with strangers particularly involving their children (iii) Technology and literacy barriers like discomfort with electronic surveys and varying literacy levels among participants (iv) Child-centric approach of one to one conversation in the presence of parents fostered a sense of security and comfort for children. (v) Comprehensive spatial coverage was important to ensure a representative sample across the neighbourhood's diverse physical environment. A door-to-door approach,

coupled with clear explanations about the study's purpose and data usage, a conversational way of interview, flexibility in language choice (Hindi, Marathi, or English), employing young adult interviewers (aged 20-25) allowed to build trust, put children at ease, established rapport with both children and parents helped more open and engaging data collection method. After the consent was secured from both the parent and the child, the interview surveys were conducted in the presence of parents in the language of choice and lasted 15-20 min. The questionnaire included 13 questions and 4 subscales, adapted from internationally and nationally recognised scales. (Adlakha *et al.,* 2016; Bringolf-Isler *et al.*, 2012; Cain *et al.*, 2021; Huang *et al.,* 2009; Islam, 2008; Kyttä *et al.,* 2012; Mehreen *et al.,* 2020; Rosenberg *et al.,* 2009; Telford *et al.,* 2004; Tetali *et al.,* 2015; Thomson *et al.,* 2018) The residential address provided by the parents was re-checked using Google Earth and Google Street View and confirmed by the parents or by direct observation.

Objective data

For collecting the objective data of outdoor physical environment characteristics, a Geographic Information System (GIS) was employed due to its inherent capabilities in spatial data creation, management, integration of various datasets and analysis. GIS was instrumental in precise measurements and mapping of PE features like building footprints, areas of ROS, and linear measurements. It facilitated a comprehensive understanding of physical environment features. A circular neighbourhood buffer of a 400-meter radius was created around each child's (N=70) home location to compute GIS data of objective measures of OPE. This definition of individual neighbourhood buffer is similar to several international studies and national studies of the same genre. (Kyttä *et al.,* 2012; Tyagi & Raheja, 2021) GIS data extraction was a three-step process as explained herein.(Brisotto *et al.,* 2023; Pindarwati & Wijayanto, 2023)

(Step-1)-***Base data collection:*** The building footprint was generated from Google satellite imagery using Mapflow AI (https://mapflow.ai/), a machine learning algorithm for automated feature extraction. OpenStreetMap, Google Street View and Google Maps /Earth were used to create vector data for locating the participant's home and buffering, identifying the road categories, marking the footpath, land use and recreation open spaces. (Step-2)- ***Augmentation:*** To enhance and refine the base data, Google Street View and Ground Truthing process (direct observation, photo documentation) were used for attribute addition like building type, number of stories, and quality audit of recreation open spaces. (Step-3)- ***Analysis:*** Spatial analysis and map creation were performed using QGIS (version 3.24) geographic information system software (QGIS Development Team, 2021). Intersection analysis was done to calculate road intersection density. Pivot tables were used for summarising and aggregating the data. Data output tables were used for further analysis.

RESULT AND DISCUSSION

Analysis

Statistical analysis was performed using IBM SPSS Statistics version 26. To confirm the difference in OPE characteristics across the three neighbourhoods analysis of variance was performed using a one-way ANOVA Test (for normally distributed variables) and Krukal-Wallis Test (for non-normally distributed variables). Bivariate correlation analysis and multiple linear regression were used to investigate the association between children's social connectedness and objective and perceived OPE characteristics, personal characteristics of gender), and other factors like mode of travel to school, and license for IM. Several studies from Asia have employed a similar approach to examine built environment influence on children's outdoor PA (Islam, 2008; Islam *et al.,* 2016), children's independent mobility (Tyagi & Raheja, 2021) and time spent outdoor (Islam *et al.,* 2016) Other international studies have also employed similar statistical strategies to examine the influence of OPE characteristics on children's various developmental outcomes like PA, AT and IM (Oliver *et al.,* 2015b; Timperio *et al.,* 2008; Tyagi & Raheja, 2021)

1) Children's Social Connectedness by Gender

This section presents the outcome of descriptive statistics analysis of subjectively measured variables (Mean, SD) for the overall sample (N=70) and separately for boys (N=35) and girls (N=35). The outcome of ANOVA (Independent sample t-test, Chi2 test) of social connectedness and other subjective variables by gender is also included. (See Table 3). Age and Monthly Household Income variables were considered only for recruitment purposes and not included in the correlation analysis as independent variables. Overall, children reported a moderate level of social connectedness (mean=7.68, Maxi score=20) and 4.4 number

of friends, 2.57 number of known adults and perceived their friendships as moderate quality (mean=5.2, Maxi score=10). Boys consistently report higher mean scores for social connectedness (8.61 vs 6.75) and its three dimensions (Ref. Table 2) as compared to girls. The difference in the social connectedness of boys and girls was significant (t = 2.92, p= 0.005) with medium to large effect size (Cohen's d=0.7). Overall children acquired 54.77 minutes of OOPA per day. Whereas boys were acquiring substantially higher amounts of OOPA per day in a week than girls. (72.94 minutes vs 36.6 minutes) and this difference is statistically significant (t = 4.57, p-values <0.05) with a large effect size. (Cohen's d =1.09). Children have similar perceptions about traffic (Mean:2.29) and personal (Mean: 2.0) safety in the neighbourhood.

The Gender differences found in perceptions of traffic and personal safety were statistically not significant. (p-values >0.05). Boys find their neighbourhoods significantly more favourable for outdoor physical activities as compared to girls (p-values <0.05) and large effect size (Cohen's d =0.7). Predominantly children used passive mode (78.57%) of travel to school as compared to active mode (21.43%). Mode of travel showed an insignificant but weak association with gender. (p-values >0.05 and Phi = 0.103). More than half the children report high levels of independent mobility (Mean:57.14) as compared to moderate or some mobility (Mean:25.71) or no mobility (Mean: 17.14). With the current sample size, there was not enough evidence found to associate licence for independent mobility with gender (p-values >0.05 and Phi=0.056).

Table 1: Physical Profile of Three Neighbourhoods

Character	TN (N=25)	JP (N=18)	BS (N=27)
Location	South –West	North	South –East
Age of locality in years	40-30	60-50	<15
	Low-rise upto (G+3)	Low-rise upto (G+3)	Mid Rise upto (G+4 to G+8)
Street pattern	Irregular grid partially disconnected	Regular grid connected	Fragmented grid
Stage of development	Developed	Redevelopment initiated	Developing
Socio-economic character	MIG-I-II, LIG Monoculture Maharashtrian community	MIG-I-II, LIG Mixed culture North Indians, Maharashtrian, Buddhist	MIG-I-II, Mixed culture North &South Indians, Maharashtrian

Table 2: Outdoor Physical Environment Variables[1]

Attributes	Variable	Measurement/Indicator (Formula/Scale)	Source/ Tool
1) Built Form	1) Built-up area density[2]	Built-up area ratio (Gross floor area of all buildings / Total land area in 400 M. buffer) Unit: Area in SQM	GIS analysis
	2) Land use mix [3]	Entropy index: (Ratio calculated for six land uses residential, commercial, mixed-use, institutional, recreation open spaces, and other open spaces)	GIS analysis
2) Vehicular network	3) Street connectivity[4]	Intersection density[3]: Count of 3 or more legged intersections in 400 M. buffer Unit: Count in numbers	GIS anaysis

(Table 2 Contd ....)

Footnotes:

[1] Outdoor physical environment variables: (Cain *et al.,* 2021; Davison & Lawson, 2006; Ding *et al.,* 2011; Loon & Frank, 2011; Sterdt *et al.,* 2014)

[2] Built-up area density is measured as the built-up area ratio. (Islam, 2008)

[3] Land-use mix is represented by the entropy index, which is the most commonly used and widely accepted index. It is an evenness distribution of the proportion of the estimated square footage/ floor space of different land uses within the buffers using the following formula known as the Entropy index. (Nordbø *et al.,* 2018; Tyagi & Raheja, 2021)

[4] Intersection density is a measure of connectivity of the street network. (Frank *et al.,* 2005; Oliver *et al.,* 2015a)

(.... Contd Table 2)

	4) Traffic exposure[5]	The ratio of high-speed roads: (Total length of high-speed roads / Total length of low-speed roads in 400 M. buffer)	GIS analysis
3) Pedestrian and cycling infrastructure	5) Footpath availability[6]	The ratio of roads with footpaths: (Total length of roads with a footpath / Total length of all the rods in the 400 meter buffer)	GIS analysis
	6) Utility of pedestrian and cycling infrastructure[7]	Sub-scale: (6 items) (1) Frequency of footpath use (1 item) (2) Barriers to use of footpath (4 items) (3) Barriers to cycling (1 item) Response: 4-point Likert scale (strongly disagree=1 and strongly agree=4)	Survey
4) Recreation open spaces(ROS)	7) Proximity to ROS[8]	Street network distance to nearest ROS from home Unit: Distance in Meters	GIS analysis
	8) Amount of ROS[9]	The total area of ROS within 400 M buffer in SQM Unit: Area in SQM	GIS analysis
	9) Number of ROS[10]	Count of ROS within 400 M buffer Unit: Count in numbers	GIS analysis
	10) Quality of ROS[11]	A quality audit was conducted for 5 ROS features. (1) Access and surrounding (2) Play facilities. (3) Amenities (4) Aesthetic features (5) Safety Unit: Sum of quality audit score of all the ROS in the 400 M buffer	Quality audit
5) Perception of safety in the neighbourhood	11) Traffic safety[12]	Subscale- 1 items Response: 4-point Likert scale (strongly disagree=1 and strongly agree=4)	Survey
	12) Personal safety[13]	Subscale- 1 items Response: 4-point Likert scale (strongly disagree=1 and strongly agree=4)	Survey
6) Perception of neighbourhood environment for PA	Presence of PA facilities and PA culture in the neighbourhood.[14]	Sub-scale (4 items) (1) Level of satisfaction with PA facilities in the neighbourhood (1 item) (2) Presence of PA culture and friendliness in the neighbourhood (3 items) Response: 4-point Likert scale (strongly disagree=1 and strongly agree=4)	Survey Survey

Reference: Author

Footnotes:

[5] Traffic exposure is measured as the ratio of high-speed road length to low-speed road length. In the absence of traffic volume data, the traffic function was used as a proxy and traffic speed exposure. The data on the design speed of four urban roads (arterial, sub-arterial, collector and local) were obtained from the Indian Road Congress manual IRC:86-1983. The arterial and sub-arterial roads formed the category of high-speed roads (>50 km/h) and collector and local rods formed the category of low-speed roads (<50km/h). (Adlakha *et al.*, 2016; Cerin *et al.*, 2019; Day *et al.*, 2015; Giles-Corti *et al.*, 2011) (Geometric design standard for urban roads in plains, IRC, 1983).

[6] Footpath availability: (Brownson *et al.*, 2009)

[7] Utility of pedestrian and cycling infrastructure: (Adlakha *et al.*, 2016; Cerin *et al.*, 2019; Day *et al.*, 2015)

[8] Proximity to ROS; (Davison & Lawson, 2006; Koohsari *et al.*, 2015)

[9] Amount of ROS8; (Kaczynski *et al.*, 2020)

[10] No of ROS; (Kaczynski *et al.*, 2020)

[11] Quality of ROS (Kaczynski *et al.*, 2020; Saelens *et al.*, 2006)

[12] Traffic safety: (Rosenberg *et al.*, 2009; Timperio, 2004)

[13] Personal safety: (Rosenberg *et al.*, 2009; Timperio, 2004)

[14] PA environment in the neighbourhood : (Holt *et al.*, 2008; Wong *et al.*, 2010)

Table 3: Descriptive Information and Analysis of Variance by Gender for Subjective Measures. (Independent Sample t-test, Chi2 test)

Variable	Overall (N - 70) *Mean (SD)*	Independent sample t-test			
		Girls (N=35) *Mean (SD)*	Boys (N=35) *Mean (SD)*	*t (df)*	*Chhen'sd*
1. Social connectedness (SC)	7.68 (2.8)	6.75(2.56)	8.61 (2.76)	2.92** (68)	0.7
Number of friends in the neighbourhood	4.4 (2.22)	3.8(2.29)	5.0 (2.01)	2.33* (68)	0.56
Friendship quality	5.2 (2.23)	4.42 (1.91)	5.98 (2.28)	3.1** (68)	0.74
Number of known adults in the Neighbourhood	2.57 (1.48)	2.0 (1.06)	3.14 (1.63)	3.48**(68)	0.83
2. Outdoor out-of-school PA (OOPA	54.77(37.76)	36.6 (20.32)	72.94(42.44)	4.57**(68)	1.09
3. Children's Perception of safety in the neighbourhood					
Traffic safety	2.29 (0.93)	2.17 (1.01)	2.4 (0.85)	1.02 ^{ns} (68)	0.24
Personal safety	2(0.99)	2.0 (1.06)	2.0 (0.94)	0 ^{ns} (68)	0
4. Perception of the PA environment in neighbourhood	5.66(1.33)	5.22 (1.20)	6.1 (1.33)	2.93**(68)	0.7
Variable	Overall (N=70) (%)	Girls (N=35) (%)	Boys (N=35) (%)	Chi2 test	
				X^2 (df)	Phi
5. Mode of travel to school					
Active mode (%)	21.43	12.86	8.57	0.76^{ns}(1)	0.103
Passive mode (%)	78.57	37.14	41.13		
6. License for independent mobility					
No IM (%)	17.14	10	7.14	3.93^{ns} (2)	0.056
Some IM (%)	25.71	17.14	8.57		
High IM (%)	57.14	22.86	34.29		

Reference: *Author, Notes: (1) (*p<0.05, **p<0.01), (2) n.s. indicates non-significant correlations (p>0.05)*

Table 4: Descriptive Information and Analysis of Variance by Neighbourhoods (TN, JP and BS) for Subjective and Objective Measures. (One way ANOVA, Chi2 test).

Subjective Variable	*One way ANOVA*				
	TN (N=25) *Mean (SD)*	JP (N=18) *Mean (SD)*	BS (N=27) *Mean (SD)*	*F (df1, df²)*	*Eta Squared (n^2)*
1. Social connectedness (SC)	8.86 (2.13)	9.2 (3.09)	5.57 (1.67)	19.13 ** (2,67)	0.36
Number of friends in the neighbourhood	4.84 (2.3)	5.5 (2.36)	3.26 (1.48)	7.41** (2,67)	0.18
Friendship quality	6.81 (1.77)	6.2 (1.55)	3.04 (0.85)	52.1** (2,67)	0.61
Number of known adults in the Neighbourhood	2.48 (0.92)	3.89 (1.45)	1.78 (1.34)	15.81* (2,67)	0.32
2. Outdoor out-of-school PA (OOPA)	56.16 (33.28)	75.4 (51.13)	39.7 (22.79)	5.5** (2,67)	0.14
4. Children's Perception of safety in the neighbourhood					
Traffic safety	2.52 (0.82)	2.44 (0.78)	1.96 (1.06)	2.79** (2,67)	0.08
Personal safety	2.52 (0.92)	2.06 (0.94)	1.48 (1.85)	8.74* (2,67)	0.21
5. Perception of the PA environment in neighbourhood	6.41 (0.94)	5.83 (1.18)	4.85 (1.32)	11.92* (2,67)	0.26
6. OPE characteristics					

(Table 4 Contd ....)

(.... Contd Table 4)

Subjective Variable	One way ANOVA				
	TN (N=25) *Mean (SD)*	JP (N=18) *Mean (SD)*	BS (N=27) *Mean (SD)*	*F (df1, df²)*	*Eta Squared (n²)*
1. Built form					
Built-up area density	0.80, (0.07)	0.89, (0.19)	0.53, (0.13)	46.94** (2,67)	0.58
Land use mix	0.41,(0.09)	0.43, (0.06)	0.60, (0.14)	24.62** (2,67)	0.42
2. Vehicular network					
Street connectivity	284, (72.79)	263, (34.31)	59, (17)	168.29**(2,67)	0.83
Traffic exposure	0.16,(0.05)	0.06, (0.05)	0.02, (0.04)	62.89** (2,67)	0.65
3. Pedestrian and cycling infrastructure					
Footpath availability	0.41(0.05)	0.3 (0.06)	0.13 (0.07)	138.18* (2,67)	0.8
Utility of pedestrian and cycling infrastructure[1]	6.77 (0.77)	7.02 (1.81)	3.37 (1.62)	49.51* (2,67)	0.6
4. Recreation open spaces (ROS)					
Proximity to ROS	231 (86.24)	227 (113.46)	290 (189.1)	1.44^{ns} (2,67)	0.04
Number of ROS	5.5 (2.04)	3.89 (1.28)	2.96 (1.09)	16.99* (2,67)	0.34
Quality of ROS	267.12, (75.15)	158.57 (86.28)	88.53, (31.91)	48.45** (2,67)	0.59
Area of ROS	33449.04 (10797.11)	19223.28, (13862.92)	9064.04 (7486.98)	34.52** (2,67)	0.51
Nominal/ Ordinal Variable	**TN (N=25) *(%)***	**JP (N=18) *(%)***	**BS (N=27) *(%)***	*Chi2 test*	
				X² (df)	**Cramer's V**
7. Mode of travel to school					
Active mode	10	10	1.43	8.94* (2)	0.357
Passive mode	25.71	15.71	37.14		
7. License for independent mobility					
No IM	10	1.43	5.71	15.58** (4)	0.33
Some IM	2.86	4.29	18.57		
High IM (%)	22.86	20	14.29		

Reference: Author, Notes: (1) (*p<0.05, **p<0.01), (2) n.s. indicates non-significant correlations (p>0.05)

The above results showed a potential gender difference in social connectedness and its linked dimensions. Mitic, (Mitic *et al.,* 2021 Wave higher-quality friendships than boys. Results have demonstrated gender differences also in OOPA (Anderssen & Wold, 1992; Sallis *et al.,* 2000) and perceptions of the supportiveness of the neighbourhood for physical activity (Mecredy *et al.,* 2011) This suggests that gender is an important factor to consider in the investigation of the relationship between neighbourhood PE and the social connectedness of children. (Ashiabi & O'Neal, 2015; Bronfenbrenner & Ceci, 1994)

2) Children's Social Connectedness Across Neighbourhoods

This section presents descriptive statistics analysis (mean, SD) and the results of ANOVA (one-way ANOVA, Chi2 test) of objective variables and subjective variables of OPE across three neighbourhoods (TN, JP and BS) (See Table 4)

Children from JP (8.61) reported the highest levels of social connectedness followed by TN (6.75) and BS (2.92). Significant difference exit in SC across neighbourhoods (F=10.13, p=<0.001, n2=0.36). Similar to SC, children from

Footnote:

[1] A survey questionnaire measured Outdoor physical environment variables subjectively

JP reported having the most friends (5.5) and know most adults (3.89) in the neighbourhood followed by TN (Friends: 4.84, Adults: 2.48) and BS (Friends: 3.26, Adults: 1.78). There was a statistically significant difference in number of friends (F=7.41, p=0.001, n2=0.18). and number of known adults (F=15.81, p=<0.001, n2=0.32). Children from TN (6.81) report the highest mean score of friendship quality followed by JP (6.2) and BS (3.04) and the difference is statistically significant across the neighbourhoods (F=52.1, p=<0.001, n2=0.61).

3) Preliminary Insight into OPE and other Pathways Influencing Children's Social Connectedness

Spearman's ranked-order correlation analysis was performed for the entire sample (N=70) to identify and examine the strength and direction of the relationship of OPE variables (both subjective and objective measures) with children's social connectedness (SC), The significant correlations identified from this analysis are presented in (Table 5). Taking into account the preliminary exploratory nature of this pilot study which was expected to inform further research, the correlation results are discussed here by integrating the outcome of descriptive, ANOVA (Table 3&4) and correlation analysis (Table 5) in an interpretive manner

1. OPE Profile Across the Neighbourhoods

The cluster analysis done for the neighbourhood selection was based on limited data. Understanding the detailed physical profile of the neighbourhood was important to interpret the descriptive, ANOVA and correlation analysis results comprehensively. Hence, the hierarchical cluster analysis was performed again using the GIS data of six OPE characters computed within a 400-meter buffer around each child's home. (N-70). The dendrogram based on mean, median and SD values of four OPE factors reveals the following neighbourhood clustering pattern. (See Figure-2) The OPE profile of the three neighbourhoods has been comprehensively interpreted with the help of cluster dendrogram (Figure 2), descriptive statistics (Table 4), and observed characteristics of the neighbourhood (Table 1) as follows.

Jaripatka (JP) is the oldest (60-50 years old) neighbourhood with a higher density(0.89)and land-use mix (0.49). It has marginally lower street connectivity (263 intersection / sqkm) and traffic exposure (0.06) compared to TN and has a moderate amount of ROS (19233 sq.m/sqkm) of moderate quality (158.57). JP is also undergoing partial redevelopment, implying a transition in its built form potentially towards mixed land use.

Whereas, Trimurti Nagar (TN) (40-30 years old), with its marginally lower built-up area density (0.8) and land-use mix (0.41) than JP, has higher street connectivity (284 intersections / sqkm) and traffic exposure (0.06) than JP. TN has ample ROS (33,449 sqm/sqkm) of high-quality facilities and amenities. (262.12). TN has a well-established infrastructure, reflecting its developed stage.

Besa neighbourhood, (<15 years old) has a low density (0.53), less street connectivity (59 intersections / sqkm) and a meagre amount of ROS (9064 sqm/sqkm) of the lowest quality (88.53). BS has the highest land-use mix (0.6) among the three neighbourhoods, suggesting a wide variety of land uses. The low density and high land-use mix of the BS neighbourhood indicates large parcels of vacant land. Overall, it suggests that BS is a relatively new and still-developing neighbourhood.

In conclusion, JP and TN are more similar in their OPE character and clustered together first. (figure 2). Both have similar built forms (built density, land-use mix and street connectivity) but differ in terms of exposure to heavy traffic and characteristics of ROS. BS has the most distinct OPE character compared to the other two. The re-analysis served to confirm the stability of the initial clusters and strengthened the validity of the study findings

2. Oopa as a Potential Pathway Linking OPE and Children's Social Connectedness

OOPA has demonstrated a high-moderate correlation (0.03<r> 0.5, P<0.01) with SC and its three sub-variables. (Table-5) which was consistent with Bronfenbrenner's preposition that the reciprocally interactive proximal processes are the mechanisms through which developmental potentials are actualised. (Ashiabi & O'Neal, 2015; Bronfenbrenner & Ceci, 1994) Literature has ample evidence of friendships and social interactions positively contributing to children's PA, AT and well-being. (Jago *et al.,* 2011; Sharma *et al.,* 2009; Wray *et al.,* 2020) and conversely, PA benefits various aspects of children's social development such as peer friendships, social interaction and integration, and social skills. (Holt *et al.*, 2011; Howie *et al.*, 2010) Moreover, existing literature supports the positive association of children's participation in PA (recreational and travel PA) with various neighbourhood PE factors

and characteristics like density, land use mix, (Frank *et al.*, 2007), access to child-specific destinations like schools, recreation facilities (Giles-Corti *et al.,* 2011; Timperio *et al.*, 2008), street Connectivity (Roemmich *et al.*, 2007), traffic Exposure, (Davison & Lawson, 2006), pedestrian and cycling infrastructure (Smith *et al., 2*017), and perceptions of safety and neighbourhood PA facilities. (Sallis *et al.*, 2000; Timperio, 2004) The convergence of previous research and the present study's preliminary analysis findings emphasises the potential role of OOPA as a pathway linking OPE and SC and upholds the key proposition of this study that children's OOPA was a significant social activity through which various social developmental outcomes are actualised enabling social connectedness. (Abdollahi *et al.,* 2023; Rogers, 2012)

3. OPE Pthways to Children's Social Connectedness

(a) Built from: The correlation analysis has revealed several significant strong to moderate correlations between OPE characteristics and SC and its related three dimensions. (number of friends, friendship quality and, known adults) ($0.3 < r > 0.05$, $p<0.001$) (Table 5). As hypothesised built area density and street connectivity were found to be positively correlated with SC. However, the negative correlation of land-use mix with SC is unexpected as per existing literature. (Abdollahi *et al.,* 2023)

Higher values of these core features of urban form variables are indicative of compact urban forms and concentrated urban activities. High density means closely clustered dwellings, higher concentration of people and more number of children to play with, increased physical proximity and social contacts enhancing the possibility of children having greater peer and intergenerational social networks. (Christian *et al.,* 2015; Mouratidis, 2018) A higher land-use mix indicates greater availability of neighbourhood destinations to visit (recreational and utilitarian), creating opportunities for children for social interactions and activities. (Abdollahi *et al.,* 2023; Loebach & Gilliland, 2022) A highly interconnected street network implies direct and more alternate routes improving proximity to various children's neighbourhood destinations. (Davison & Lawson, 2006; Oliver *et al.,* 2015a) In conclusion, the synergetic effect of compact built form enhances walkability, use of recreational spaces, and visits to other destinations and creates opportunities for children's social interaction, activities and independent mobility. Many previous studies have recognised the potential of these three core built-form features. (Abdollahi *et al.,* 2023; Frank *et al.,* 2007) In the present study, 61% (N= 43) of the children reside in TN and JP neighbourhoods, which have distinctly higher built-density and street connectivity compared to BS. (Table 4) Children from JP demonstrate the highest levels of social connectedness, number of friends and known adults closely followed by TN with marginally lower levels. Children living in BS, which is a sparsely built neighbourhood, show a low level of SC and its related dimensions among children. These findings are supported by previous research. (Abdollahi *et al.,* 2023; Frank et al., 2007).

Several factors may account for the negative association found between land use mix and children's SC in all three neighbourhoods in this study. Nagpur's long-standing history of city planning has resulted in the prevalence of mixed land-use planning and it continues to present-day planning practices of transit-oriented development. This ubiquity makes it challenging to detect the specific influence of land-use mix in any single area. The urban fringe neighbourhoods like BS have sprawling built forms but have the highest level of land-use mix. However, children can not leverage the benefits of a high land-use mix because of lower levels of residential density, street connectivity and underdeveloped pedestrian infrastructure and recreation spaces. Moreover, BS land use is characterised by large parcels of vacant lands, large commercial establishments, service-oriented businesses and construction material retail does not create social opportunities for children.

The redevelopment and densification process is already underway in JP where ad-hoc integration of commercial and mixed-use within residential areas has resulted in traffic congestion and encroachment of commercial activities and parking on roads and side footpaths, creating major obstacles for children's outdoor play and active travel and indirectly influences their social connectedness. The TN neighbourhood which was developed during the period of expansion of institutional housing shows the more planned approach to implementing a land-use mix. The main commercial use is located along the peripheral roads. The overall street network is better designed. This configuration may be more conducive to children's social connectedness.

Our, analysis reveals that even though a mixed Land-use planning pattern is prevalent in Nagpur and India, its advantages can not be obtained for improving children's SC unless its planning, execution, maintenance, its relationship with other OPE features and spatial configuration are subject to ongoing appraisal.

(b) Transport: Transport can influence children's PA and social health through two primary ways, exposure to traffic and mode of travel (Abdollahi *et al.,* 2023)

(c) Traffic exposure: Traffic exposure showed a significant positive association with SC and quality of friendships which was not consistent with anticipated results (See Table 5). Acknowledging the data limitations of this pilot study a tentative explanation for this phenomenon can be given as follows. ANOVA indicates that TN and JP (61% of the total sample) have similar built-form characteristics which are distinctly different from BS (Post-hoc tests, all adj. $p < 0.05$) (See Table 4). The traffic exposure significantly differs among the three neighbourhoods. (Post-hoc tests, all adj. $p < 0.05$). Notably, TN has a significantly higher proportion of high-speed roads. (Adj. $p<0.001$) compared to JP and BS, but the difference in children's perception of traffic safety is non-significant.

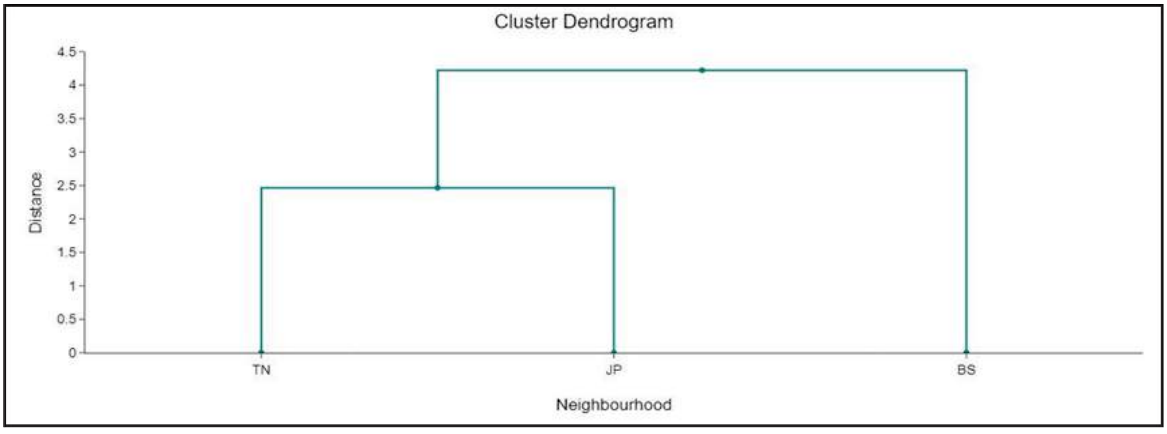

Fig. 2: Hierarchical cluster analysis: Dendrogram of three Neighbourhoods for OPE factors

Reference: *(Statistical analysis using SPSS ver. 26.0.0); (Data visualization: DATAtab (DATAtab Team, 2024).*

Table 5: Association between social connectedness and outdoor physical environment characteristics of the neighbourhood.

Variables	Social connectedness	No. of friends	Friendship quality	Number of known adults
OPE characteristics	Spearman's Rank-Order Correlations (r, p-value)			
1. Built-up-area-density	**0.55****	0.41**	**0.65****	0.38**
2. Land-use-mix	**-0.45****	-0.33**	-0.49 **	-0.29**
3. Street connectivity	**0.52****	0.35**	**0.61****	0.28*
4. Traffic Exposure	**0.36****	ns	**0.58****	ns
5. Footpath availability	**0.51****	0.34 **	**0.7*****	0.220*
6. Utility of pedestrian and cycling infrastructure	**0.53****	0.39 **	**0.65*****	0.37**
7. Proximity to ROS in buffer	ns	ns	ns	ns
8. Number of ROS in buffer	0.26 *	ns	0.35**	ns
9. Amount of ROS in buffer	0.34**	ns	0.41**	ns
10. Quality of ROS	0.42**	0.24*	0.49**	ns

(Table 5 Contd ....)

(.... Contd Table 5)

11. Perception of Traffic safety	0.24*	ns	0.33**	ns
12. Perception of Personal Safety	ns	ns	0.39**	ns
13. Perception of PA environment in the neighbourhood	**0.50****	0.44**	**0.50****	0.30*
Personal characteristics and other factors				
14. Outdoor out of school PA	**0.57****	**0.54** **	0.42 **	0.47**
15. Motivation for PA	**0.65** **	0.49 **	**0.72** **	0.47 **
Point-biserial Correlation (rpb,p-value)				
16. Gender	0.33**	0.27*	0.35**	0.39**
17. Mode of travel to school	ns	0.31**	0.35**	ns
Eta Correlations (n, p-value)				
18. Licence for IM	0.41*	0.45*	0.38*	0.32*

In all three neighbourhoods, the high-speed roads are on the periphery and it did not appear to adversely influence children's perception of traffic safety implying it was positively contributing to children's SC. As noted previously, JP has a relatively more compact built form and mixed community character. Previous studies have suggested that that it favours more vibrancy of activities and supports social cohesion thus fostering a socially interactive environment and incidental community connections. (Kotharkar *et al.,* 2014; Waygood & Friman, 2015). However, we find that children from TN though exposed to high traffic have better SC and friendship quality than JP. This finding is similar to Waygood's *et al.,* (2017) study investigating the relationship between children's mode of travel and incidental social interactions which suggests that active travel regardless of traffic exposure increases incidental social interactions. Furthermore, we note that even though slow, the traffic congestion on the access roads might hinder children's mobility as in the case of JP, where densification and redevelopment are already emerging but not effectively managed.

(d) Travel: Active travel to school and license for independent mobility: The data of the present study demonstrated the insignificant difference in the active travel (AT) mode to school and licence for independent mobility (IM) by gender. However, there was a significant difference in AT to school ($F=8.94$, $p<0.05$) and in the licence for IM ($F=15.58$, $p<0.05$) across the neighbourhood. Given the significant difference in the OPE characteristics across the neighbourhoods, the variation in AT and IM was expected and it is supported by existing literature.
(Frank *et al.,* 2007; Tyagi & Raheja, 2021)

Correlation analysis showed that AT to school has a moderate association with, the number of friends ($r= 0.31$, $p=<0.05$) and quality of friendships ($r = 0.35$, $p=<0.05$) and had no considerable association with overall SC and the number of known adults. (See Table5) Very few from TN and JP (10% each) and just a minuscule (1.46%) number of children use AT mode to school. The lack of significant association between AT to school and overall SC or the number of known adults may be because, in Nagpur, children commonly attend schools outside their neighbourhood and use passive modes of transport and clock in longer time commuting to schools. Potentially reducing their opportunities to interact with neighbourhood peers and neighbours. (Tyagi & Raheja, 2021) However, licenses for children's IM showed a consistently significant moderate correlation with overall SC ($r= 0.41$, $p=<0.05$), the number of friends ($r= 0.45$, $p=<0.05$), quality of friendships ($r = 0.38$, $p=<0.05$), the number of known adults ($r = 0.32$, $p=<0.05$). Even though TN has well well-developed infrastructure, the proportion of children having no IM is higher (10%) as compared to JP (1.43%) and BS (5.71%)

PE characteristics influence children's travel behaviour and collectively create various conditions

that may be linked to various positive developmental outcomes. (Panter *et al.,* 2010; Schoeppe *et al.,* 2013) Active and independent travel naturally aligns with the children's developmental need for competence and independence and fosters deeper connections with the surrounding physical and social environment. (Eccles, 1999) Though children's active independent mobility is frequently linked with PA (Giles-Corti *et al.,* 2005; Panter *et al.,* 2010), its social developmental benefits are relatively less investigated. Some studies have associated AT with more intentional and incidental social interactions during the journey strengthing their peer friendships and community connections. (Waygood *et al.,* 2017; Waygood *et al.,* 2021). Studies investigating IM link it with increased peer activities, self-confidence, sense of community and safety, contributing to the feeling of connection with peers and community. (Pacilli *et al.,* 2013).

Given the neighbourhood profile discussed earlier in this paper, though TN has a relatively well-developed infrastructure, JP with its comparatively deficient infrastructure yet compact built form, and vibrant street life, is more socially engaged, with more eyes on the streets and seems to be more conducive for children to actively travelling to school. In the context of neighbourhoods in Nagpur, children's IM proved to be a potential pathway to enhance children's SC. Some other previous studies have reported similar findings. (Kyttä, 2004; Tyagi & Raheja, 2020; Waygood *et al.*, 2017)

(e) Pedestrian infrastructure: Neighbourhood-level infrastructure deprivation is widely prevalent in Indian urban neighbourhoods (Dutta *et al.,* 2017) A recent report on walkability research report in Nagpur, states that 73% of footpaths are not used by children which is a concerning indicator of infrastructure conditions. This report describes pedestrian infrastructure problems like incomplete, discontinuous design, narrow widths, encroachment, litter, and neglected maintenance. (ESAF & Health Bridge, 2015-2016) In a situation where walking on the footpaths becomes a task for the children, it is essential to understand how it influences children's PA and SC. The ANOVA results demonstrate a significant difference in footpath availability ($F=139.18$, $p<0.05$) and the utility of pedestrian and cycling infrastructure ($F=49.51$, $p<0.05$) (See Table 5). The large effect size ($n2= >0.35$ for both) suggests both these OPE characteristics are distinguishing features among the three neighbourhoods. The consistency of moderate to strong correlations of availability and utility of the pedestrian and cycling infrastructure with SC and number of friends, known adults and quality of friendships (See Table 5) highlights the importance of the supportive role of pedestrian infrastructure in enhancing children's SC in all respects. OOPA is also demonstrating a significant moderate correlation with availability ($r=0.28$,$p=<0.05$) and utility ($r=0.35$, $p=<0.05$) of pedestrian infrastructure.

Similar to findings from the previous studies, these results also suggest that neighbourhoods with adequate, safe, well-mannered pedestrian infrastructure may encourage walking and cycling enhancing opportunities for social encounters and interaction fostering social connections and facilitating possibilities incidental and intentional OOPA. (Ortegon-Sanchez *et al.,* 2021; Waygood & Friman, 2015)

(f) Recreational open spaces (ROS): Building upon the earlier discussion on the PPC model and the role of OOPA as a conncetor between OPE and the social development of children, we now discuss the role of neighbourhood ROS in the interplay of OOPA and children's social lives. Though the presence of a greater number of ROS in the neighbourhood promotes non-school PA, (Timperio *et al.,* 2008) but some reviews have highlighted the mixed findings in the literature. (Koohsari *et al.,* 2015) Hence not only the presence of ROS but also the attributes like proximity, variety, quantity and quantity of ROS speculated to promote its actual use and playability are important to enhance children's physical and social activities. (Frank *et al.,* 2007)

There was no considerable neighbourhood difference in the proximity of ROS but a significant variation ($p=<0.05$) in the number, area and quality score of ROS within the 400-meter buffer from the child's home was demonstrated. The number ($r=0.25$ and $r=0.35$, $p=<0.05$) and amount of ROS ($r=0.34$ and $r=0.41$, $p=<0.05$) showed only minor to moderate correlations with children's overall SC and quality of friendships. However,

consistent significant positive correlations were observed in the quality score of ROS and children's overall social connectedness (r=0.42, p=<0.05), number of friends (r=0.24, p=<0.05), and quality of a friendship (r=0.49, p=<0.05). These findings suggested that the quality of ROS, measured as an audit assessment score of features like access and surroundings, play facilities, amenities, aesthetic features and safety are more effective in enhancing children's overall SC by contributing to the development of peer friendships.

In Indian urban neighbourhoods, a deficit in infrastructure provision and maintenance is a pervasive issue. The proximity, number and area requirements of neighbourhood ROS are partially met due to mandatory statutory regulations but the provision of age-appropriate play facilities, amenities, physical and personal safety features and general aesthetics and upkeep of ROS, which are crucial factors in stimulating children's interest and attracting them to visit ROS regularly, does not meet the required standards. (Loon & Frank, 2011) These findings are similar to previous studies drawing attention to the importance of well-maintained, safe neighbourhood ROS equipped with high-quality age-appropriate facilities to provide more diverse opportunities for peer activities like cooperative play, team sports, exploration and informal gatherings resulting in physical and social development outcomes like increased physical activeness (Cohen *et al.,* 2006; Dunton *et al.,* 2009) development of social skills, building relationships, and forming a sense of community synergetically enhancing children's social connectedness. (Loebach & Gilliland, 2022; Veitch *et al.,* 2008)

(g) Perceptions of the neighbourhood: Children's perceptions of the environment are shaped by their everyday experiences with the physical objects, social situations, obstacles and opportunities for their everyday activities in their living environment. Children's perceptions of the environment are also influenced by the child's characteristics like physical ability, social needs and motivations for PA. As per the bio-ecological model discussed earlier, it aligns with the reciprocal nature of interaction between the growing individual and their environment. (Ashiabi & O'Neal, 2015; Högman *et al.,* 2020) Perceptions of safety are often based on threats of physical harm, and incivilities, which denotes a negative appraisal of the environment which may be unfavourable for children's outdoor play and exploration, while perceptions of neighbourhood PA environment which is an assessment of satisfaction with the availability, usability of PA facilities and prevalence of the play culture in the community which stems from the positive appraisal of the environment as supportive to their outdoor physical and social activities.

(h) Perceived Personal safety: The descriptive and ANOVA analysis of children's perceptions of traffic safety demonstrated the highest mean score for TN (2.52), followed by JP (2.44) and the lowest score was achieved by BS (1.96) but this difference was not statistically significant. Perception of traffic safety was showing only weak to moderate correlations with overall SC and quality of friendships. (r = 0.24 and 0.33, P=<0.05). Perceived personal safety was highest in TN (2.52), followed by JP (2.06) and the lowest was in BS (1.48) and this difference was statistically significant. Perceived personal safety was found to correlate only with the quality of friendships (r=0.39, p=<0.05). Both the safety perceptions were found to have insignificant correlations with OOPA. These results differ from some previous studies that found a significant positive correlation between PA and traffic and the personal safety of children. (Carver *et al.,* 2008; Shortt & Ross, 2021; Timperio, 2004)

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The result was comprehensible as TN, and JP have relatively developed street and pedestrian infrastructure compared to BS and the peripheral location of high-speed roads across the neighbourhoods makes it feel safer for children to move around in the neighbourhood. Personal safety was the highest in a well-developed TN, followed by JP where there was more influx of people in the neighbourhood on account of an integrated and higher proportion of land-use mix resulting in heightened street activities. As the results suggest, neighbourhood safety perceptions do not show an effective influence on PA and SC. (Taylor *et al.,* 2018) Alton *et al.,* (2007) in a recent study exploring the effects of perceptions on children's PA, has found that though safety perceptions independently influence children's PA, it doesn't interfere with the relationship between OPE and PA. (Alton *et al.,* 2007) These research findings were similar to our findings suggesting neighbourhood safety perceptions might not be influencing children's PA and social interactions to the extent it can affect their SC. It is also widely acknowledged that children's feelings of safety are very important for their outdoor activities and neighbourhood mobility leading to more social engagement. (Carver *et al.,* 2008)

(j) Perceive neighbourhood physical activity environment: The descriptive and ANOVA analysis of children's perceptions of the neighbourhood PA environment demonstrated the highest mean score for TN (6.41), followed by JP (5.83) and the lowest score was achieved by BS (4.85) and this difference was statistically significant. (See Table 4) Correlation analysis reveals a significant moderate to strong relationship with overall social connectedness (r = 0.55), number of friends (r = 0.44), quality of friendships ((r = 0.50), and known adults (r = 0.30), (p =<0.05 for all). (See Table 5) These results were in line with the findings of the previous studies, suggesting availability and quality of neighbourhood recreation facilities positively influence children's activity levels. (Hayball *et al.,* 2018; Wong *et al.,* 2010) Neighbourhood parks and playgrounds equipped with age-appropriate play, and sports facilities are major neighbourhood attractions specifically for children in their middle childhood as they fulfil their developmental-stage specific needs of outdoor exploration and physical and social peer activities like group play, and spending time with friends. (Loebach & Gilliland, 2022; Rogers, 2012) The preceding discussion on children's perceptions of safety and supportiveness of the neighbourhood environment suggests that neighbourhood perceptions form a feedback loop. Positive neighbourhood perceptions encourage outdoor activities and social interactions, further improving children's perceptions of the OPE as a safe, enjoyable and socially stimulating place. This reciprocal reinforcing relationship is significantly effective in improving children's SC. (Motl , 2007) Moreover, integrating both objective (spatial) and subjective (perceptions) measures can provide a complete assessment of complex neighbourhood physical environments (Villanueva *et al.,* 2016) and refine the pathways in which OPE influence a child's social development.

CONCLUSION

This study was among the first to examine the complex relationship of children's social well-being with OPE of urban neighbourhoods in India. Considering the lack of previous research of a similar kind, the research was framed as an exploratory pilot study with a limited sample. The notable contribution of this study is the comprehensive operationalisation of variables within the theoretical framework of Bronfenbrennr's Process-Person-Context (PPC) model of human development. The context-specific, field-based investigation of this relationship has identified both expected and unexpected patterns of association between OPE and personal characteristics, the proximal process of OOPA and the developmental outcome of social connectedness.

The study has included both objective and subjective measures to get a comprehensive understanding of the complex spatial, socio-economic and cultural profile of the Indian urban neighbourhoods. Recalling the results, OOPA as expected has emerged as a highly effective interface between OPE and children's social activities in the form proximal process. Enjoyable PA experiences in child-friendly, safe OPE, can lead to a more positive perception of the neighbourhood environment, further encouraging children to spend more time outside, increasing social interaction and activities, and developing more social connections and bonding.

The study has identified compact built-form characteristics like built density and street connectivity as having a

significant influence on children's SC. Unexpectedly, the relationship between SC and the land-sue mix was negative and drew attention to the need for context-specific implementation and appraisal of mixed-use development or it may negatively influence social interactions.

The micro-built environment features like pedestrian infrastructure availability and utility have proved to be important factors to consider to increase children's active independent travel leading to more social connectedness. Children opting for active modes of travel seem to be affected by exogenous factors like distant school locations rather than OPE characteristics of the neighbourhood. Well-developed and compact neighbourhoods, having usable pedestrian infrastructure proved to be favourable for children's independent travel further positively influencing their SC.

The variety, size and quality of neighbourhood ROS have been identified as more important features, contributing to children's SC than just the proximity of ROS from a child's home. Positive perceptions about personal safety and supportiveness of OPE for PA were found to be instrumental in enhancing children's ˢocial connectedness. Given the exploratory nature of the pilot study, it proved instrumental in identifying useful patterns of associations between OPE characteristics and children's social well-being in the context of urban neighbourhoods in India.

In conclusion, this paper presents a case of an initial foray into the field of neighbourhood PE effects on child social well-being. Considering the fast-transforming urban environments with vast diversity in the socio-cultural, and economic pressures on development which is unique to India, particularly with its large children population, this study initiates an intense discourse on the impact of urban physical environment on child development and well-being. This study conducted in Nagpur, a case of fast transforming and expanding typical tier-II cities of India, demonstrates high relevance and potential for transformative impact.

CONFLICT OF INTEREST

No potential conflict of interest was reported by the authors

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Impact of Disasters in Shaping the Vernacular Architecture of Coastal Area

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Abstract—Coastal regions are highly vulnerable to a range of disasters, such as hurricanes, storm surges, and tsunamis. Unfortunately, the increasing sea levels caused by climate change only serve to worsen these risks, resulting in more frequent flooding and erosion. These disasters not only pose a significant threat to human settlements, ecosystems, and infrastructure along the coastlines, but also highlight the urgent need for proactive measures to ensure resilience and adaptation. One approach that has shown promise in creating a climate-resilient built environment is vernacular architecture, which is the practice of local communities using locally sourced materials. Through years of experience and attempts to mitigate against disasters, vernacular architecture has evolved to incorporate specific construction techniques and architectural features that are better equipped to withstand such events. In this article, we explored how disasters have influenced the development of vernacular architecture in coastal settlements, focusing on three case studies from countries surrounding the western ring of the Bay of Bengal like Sinhalese jungle huts in Northern Sri Lanka, Odisha in India, and Bangladesh. To understand the impact of disasters on building design, we have selected five key features for investigation such as building form and shape, angle of the roof, roof materials, overhang length, and wall protection techniques. Through our research, we have observed that certain design elements are directly related to the intensity of disasters. For example, regions with lower rainfall, such as Odisha, exhibit shorter overhang lengths (0.35-0.4 meters) compared to areas like Sinhalese and coastal Bangladesh, where overhang lengths range from 0.45-0.6 meters [3–6]. Additionally, the choice of materials is influenced by both local availability and the impact of disasters. Thatch and bamboo, for instance, are commonly used as roofing materials in coastal areas of Bangladesh, while Sinhalese utilizes coconut thatch, dried coconut leaves, bamboo, or mud bindings. These interrelationships between design features and disasters in vernacular architecture have led us to examine the guidelines provided by the United Nations Development Programme (UNDP). Remarkably, Odisha has fully embraced these guidelines, resulting in a significant reduction in cyclone-related damages over the years. By conducting a comparative assessment of disaster intensity, design features and techniques, and the UNDP guidelines, our study provides valuable insights for future architects and policymakers working on built-environment projects in coastal areas. In conclusion, the vulnerability of coastal areas to disasters necessitates the adoption of proactive measures for resilience and adaptation. Vernacular architecture, with its focus on locally sourced materials and evolved construction techniques, has proven to be an effective approach. By understanding the interplay between design features, disasters, and international guidelines, architects and policymakers can create more resilient built environments in coastal regions.

Keywords: Natural disaster, Costal area, Cyclone, Resilient built environment, Vernacular architecture.

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INTRODUCTION

Coastal regions stand at the forefront of vulnerability when it comes to a diverse array of calamities, ranging from the ferocity of hurricanes to the relentless onslaught of storm surges and tsunamis. Regretfully, the inexorable rise in sea levels, attributable to the unwavering grip of climate change, only serves to amplify these risks, perpetuating a cycle of more frequent flooding and erosion. The devastating consequences of these disasters extend far beyond the mere threat they pose to human settlements, ecosystems, and the very infrastructure lining our coastlines. Rather, they serve as a rallying cry, demanding the immediate implementation of proactive measures that ensure unwavering resilience and adaptability in the face of adversity. In this pursuit, the concept of vernacular architecture emerges as a beacon of hope, a promising approach to forging a built environment that can withstand the test of time and nature's wrath. Through the utilization of locally sourced materials and the wisdom gained from countless experiences, vernacular architecture has metamorphosed into a formidable force, boasting construction techniques and architectural features specifically engineered to defy the ravages of disaster.

The existing body of literature addressing vernacular architecture in response to frequent rainfall, severe floods, and landslides has predominantly centred around analyses in Mediterranean cities (Aktürk and Fluck 2022; Fernandes *et al.,* 2014; Al Tawayha, Braganca, and Mateus 2019). However, these studies often present generalized findings or concentrate on broader geographical regions, thereby overlooking the nuanced architectural responses observed in coastal settlements within the specific area surrounding the western ring of the Bay of Bengal. Despite a wealth of literature on disaster-resilient vernacular architecture (Sehbasaleem 2019; UNO and HORIKOSHI 2000) and its connection to environmental factors in building design, there is a noticeable absence of comprehensive analyses specifically delving into the unique architectural developments found in Sinhalese jungle huts in Northern Sri Lanka, houses in Odisha, India, and coastal houses in Bangladesh. Our study, motivated by this research gap, seeks to provide a targeted exploration into how disasters have influenced the evolution of vernacular architecture in these specific coastal settlements.

The next section delves into the methodology adopted for this research. How architectural features of vernacular buildings in our study areas varies to cope with heavy rainfall and flooding is discussed in section 3. This section is concluded with comparative assessment and discussion. Next, we investigated the impact of cyclone and floods on the architectural features through the lens of standards and guidelines. Finally, this article is concluded with discussion of future research scope.

METHODOLOGY

This article aims to explore the impact of heavy rainfall and flood in shaping the vernacular architecture of coastal area. In this context, the coastal areas around Bay of Bengal is focused as this sub-basin is the most active and produces some of the deadliest cyclones of all time (Encyclopedia Britannica 2024; Wahiduzzaman *et al.* 2022). The most intense cyclone in the bay was the 1999 Odisha cyclone. The Bay of Bengal's coast is shared among India, Bangladesh, Mynamar, Sri Lanka and western coast of Thailand. This research is limited to investigation of three areas like Sinhalese jungle huts in Northern Sri Lanka, Odisha in India, and Bangladesh represented in Figure 1 (a).

Furthermore, in order to thoroughly examine the effects of heavy rainfall on architectural design, it is crucial to carefully select various architectural features. The impact of heavy rainfall, coupled with flooding, can greatly affect the exterior of buildings and the materials used for roofs. Therefore, it is imperative to focus on wall protection from heavy rainfall. Additionally, the shape of the roof plays a vital role in facilitating smooth waterflow. In certain regions, heavy rainfall can even lead to disastrous floods, making it essential to prevent water from entering the interior space of buildings. This is where the plinth height comes into play. Consequently, a comprehensive investigation will be conducted on roofing materials and angles, innovative wall protection methodologies, plinth protection, and other elements that contribute to the overall resilience of structures in the face of these specific natural calamities.

Finally, in order to gain a comprehensive understanding of the similarities and differences among existing standards, guidelines and vernacular buildings, a thorough review was conducted. By comparing these features with established standards and guidelines, it became possible to determine whether vernacular buildings adhering to these guidelines are better equipped to withstand disasters. Ultimately, the findings of this study will provide invaluable guidelines for future architects, informing them whether modifications to existing guidelines are necessary and what aspects should be prioritized for new designs in the western ring of the Bay of Bengal coastal region. The flow chart represented in Figure 1 (b) would help readers for process of this research.

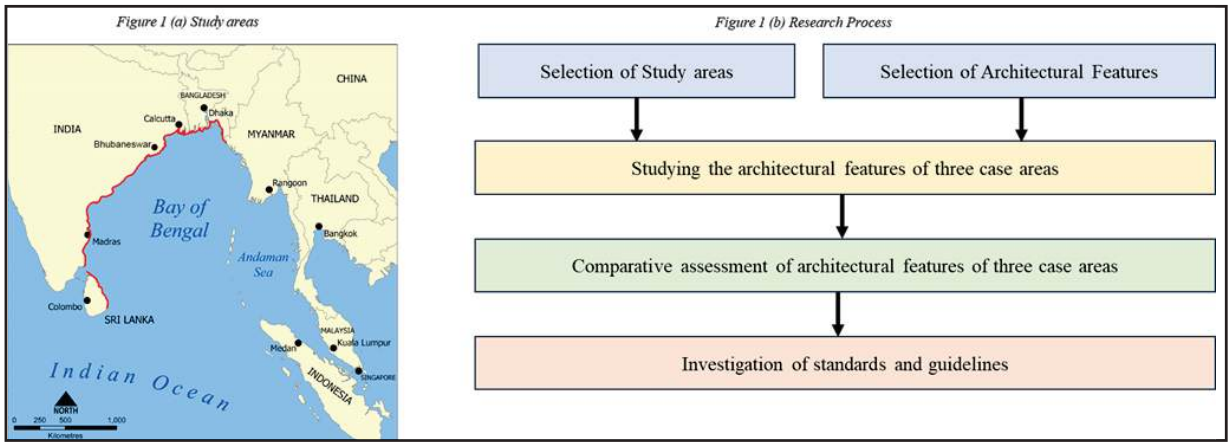

Fig. 1: Methodology

INVESTIGATION OF ARCHITECTURAL FEATURES IN RESPONSE TO CYCLONE AND FLOODS

This section is divided into two parts. The first sub-section delves into the detailed discussion on architectural features of three regions which is summarized in later sub-section.

Studying the Architectural Features

The analysis of disaster resistance concerning cyclonic storms, storm surges, and excessive rainfall and their impact on the vernacular architecture in the Bay of Bengal region is explored. The study investigates the integrated application of traditional and modern techniques to effectively mitigate and avert structural collapse. Particular attention is given to distinctive features, including the selection of roofing materials and angles, innovative wall protection methodologies, plinth protection, and other elements contributing to the overall resilience of structures in the face of such specific natural calamities.

Roof Geometry

Roof angle is a very important feature when it comes to deterrence of cyclonic storms and excess rainfall in coastal areas. A heightened roof slope promotes effective water drainage, preventing the accumulation of excess rainfall and minimizing the impact of storms. This slanted design reduces the risk of structural damage and leaks by preventing water pooling, thereby enhancing overall building resilience in the face of challenges posed by heavy rainfall and storms. The angle of roof steeps more as the annual rainfall of any area changes as it helps them to drain the excess rainfall away from the walls and house premises. The coasts of Bengal are prone to excessive rainfall and therefore the angle of the gabled roof in Bangladesh are around 42 degrees (88% grade of the roof, 10/12) as represented in Figure 2(a) and Figure 2(b) (Chowdhury 2020; Reza 2021). While as we move more towards down south, we find the angle of the roof changes, as in the houses of Odisha which is subjected to lesser rainfall the angle of the roof reduced to 34 degrees (75% grade of the roof, 8 / 12) as in Figure 2(d), however such angle also deter excess storm surges by holding them together with the roof structure (Hardy 1999). The Sinhalese jungle huts of Sri Lanka are subjected to further less annual rainfall and therefore their angle gets further reduced to 30 degrees (58% grade of the roof, 7/12) as shown in Figure 2(c) (Tucker, Gamage, and Wijeyesekera 2014).

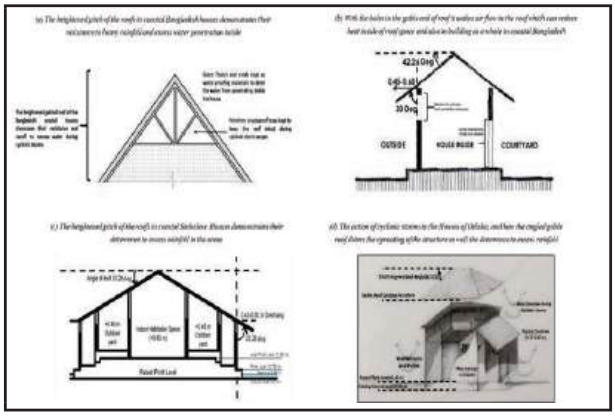

Fig. 2: Roof Geometry

Photoluminescence Study

In Bangladesh, local residents independently gather and process roofing materials like bamboo and thatch. The wisdom of construction techniques is passed down through generations, emphasizing the cost-effectiveness of employing native materials such as wood, bamboo, and thatch. Specifically, an interlocking system is utilized for materials like thatch and bamboo, forming a mesh of interconnected components. In the traditional houses of Odisha, wooden joists and purlins are paired with tin sheets using dried thatch strips. This not only strengthens the roofing, providing resilience against swift storm surges but also seamlessly incorporates contemporary materials. The tin sheets play a pivotal role in redirecting excess rainfall, averting structural damage and potential collapse. The architectural style in coastal Sri Lanka is exceptionally attuned to the tropical climate of the region. Structures are carefully designed to withstand heavy monsoon rains, strong winds, and elevated humidity, ensuring a comfortable living environment. Coastal residences often feature thatched roofs made from materials like coconut palm leaves or straw, offering natural insulation and contributing to a cool interior atmosphere amid the warm and humid coastal conditions. In some cases, the Palmyra thatch which are abundantly available in the eastern coast of Sri Lanka, dried Palmyra leaves, and mud are employed for binding in the construction process.

The effectiveness of roof overhangs in diverting excess runoff water from walls, preventing potential collapse, and occasionally facilitating groundwater recharge is pivotal in roofing. In regions with heavy rainfall, such as Bangladesh, overhang lengths typically vary from 0.45 to 0.60 meters, and some houses may feature lengths of 0.75 to 0.90 meters (usually 1.5-2.0 feet). This design is instrumental in shielding the outer walls from exposure to rainwater. Similarly, in Sri Lanka, where the climate resembles that of Bangladesh, Sinhalese jungle houses often have overhang lengths ranging from 0.45 to 0.60 meters, with some houses extending to 0.75 to 0.90 meters (usually 1.5-2.0 feet). This design strategy effectively safeguards walls against rainwater exposure and runoff, tailored to the climatic conditions of the region. In Odisha, where peak season rainfall is slightly lower, overhang lengths typically measure around 0.35 to 0.40 meters (usually 1.0-1.5 feet). Here, the incorporation of modern techniques like coal tar matting in walls allows for the potential reduction of overhang length.

Wall Protection Techniques

In Bangladesh, where houses are situated at lower elevations and in close proximity to potential flooding, dwellings in these regions are constructed using locally available materials such as bamboo matting and mud (Chowdhury 2020; Reza 2021). Mud mattings, often combined with reeds, serve as protective coverings for the walls, shielding them from the impact of heavy rainfall. To optimize construction costs, the spaces beneath the overhangs are intentionally left bare. This strategic approach not only leverages the accessibility of local resources but also minimizes expenses in vulnerable areas susceptible to flooding. In the construction of Sinhalese jungle huts in Sri Lanka, wall construction involves the daubing method (Clingen and Bavoso 2017). The cob wall technique is employed for daubing, where a mixture of mud, sand, and straw is utilized. Mud balls are closely arranged in a row to incrementally build the walls. The construction of house walls employs the cob wall technique, consisting of thoroughly mixing earth with water to achieve the desired consistency. Subsequently, mud balls are placed closely in a row to initiate and progress the wall-building process. The application of mud occurs in 2-3 layers over a span of 1-2 days. This mud matting serves the purpose of diverting excess rainwater away from the roofs. In coastal Odisha dwellings, wall coverings embrace indigenous materials tailored to the local environment. Traditional techniques involve applying mud plaster, a blend of mud, water, and occasionally additives like straw or natural fibres. This mud plaster is meticulously spread over the walls, ensuring both protection and insulation. Harvested locally, bamboo is intricately woven or affixed to walls, providing a robust and natural protective layer while contributing to the coastal aesthetic. In specific instances, houses in coastal Odisha may combine materials like mud plaster and bamboo matting to fortify walls against the region's challenging climate, marked by intense monsoons and high humidity(College of Engineering & Technology 2017). These traditional wall coverings exemplify local ingenuity in utilizing available resources to craft homes that seamlessly blend functionality with an environment suited to the coastal conditions. Figure 3 represents the wall protection techniques adopted for construction of costal houses in Bangladesh, Odisha and Sri Lanka.

Plinth Protection

The elevated plinth of Bangladesh coastal huts is designed primarily to counteract the impact of flooding and protect against rising water levels. Positioned above anticipated flood levels, this architectural approach minimizes water ingress during heavy rainfall, storm surges, or tidal activity common in coastal regions (Figure 4 (c) and Figure 4 (d)) (Chowdhury 2020; Reza 2021). The raised plinth serves as a defensive measure, shielding the interior of the huts from damage and ensuring a resilient living environment for

inhabitants. This strategic elevation is a crucial adaptation to the challenges presented by the coastal environment, enhancing the overall adaptability and durability of the structures in the face of adverse weather conditions. The usual plinth is protected using mud matting over one or two layers and over the years many layers are further added to deter water intrusion into the structure. Meanwhile in Sinhalese jungle huts, the plinth is constructed using mud or a combination of mud and wattle. The house is elevated on this plinth, typically ranging from 0.75 to 0.90 meters as shown in Figure 4 (b)(Clingen and Bavoso 2017). The plinth is adorned with finger marks in white rice paste or vertical stripes of white and red ochre, serving as a water-resistant layer to safeguard the outer part of the plinth. This elevation is strategically implemented above annual flood levels, preventing and mitigating potential submersion of the structure. Additionally, in some instances, slits made of bamboo or locally sourced palmyra timber are incorporated, further raising the structure to 1.0-1.5 meters above ground level. In Odisha, houses are elevated significantly to prevent submersion during storm surges or high tides accompanying cyclones. The raising of the structures, typically at a height of 0.75-0.85 meters above the annual flood level, acts as a protective measure against the specific challenges presented by the coastal environment as represented in Figure 4 (a) (College of Engineering & Technology 2017). This strategic elevation contributes to the overall adaptability and durability of the houses, effectively mitigating the impact of adverse weather conditions. By positioning the houses above anticipated flood levels, this architectural practice ensures better resilience and mitigation against inundation during heavy rainfall, storm surges, or tidal activity.

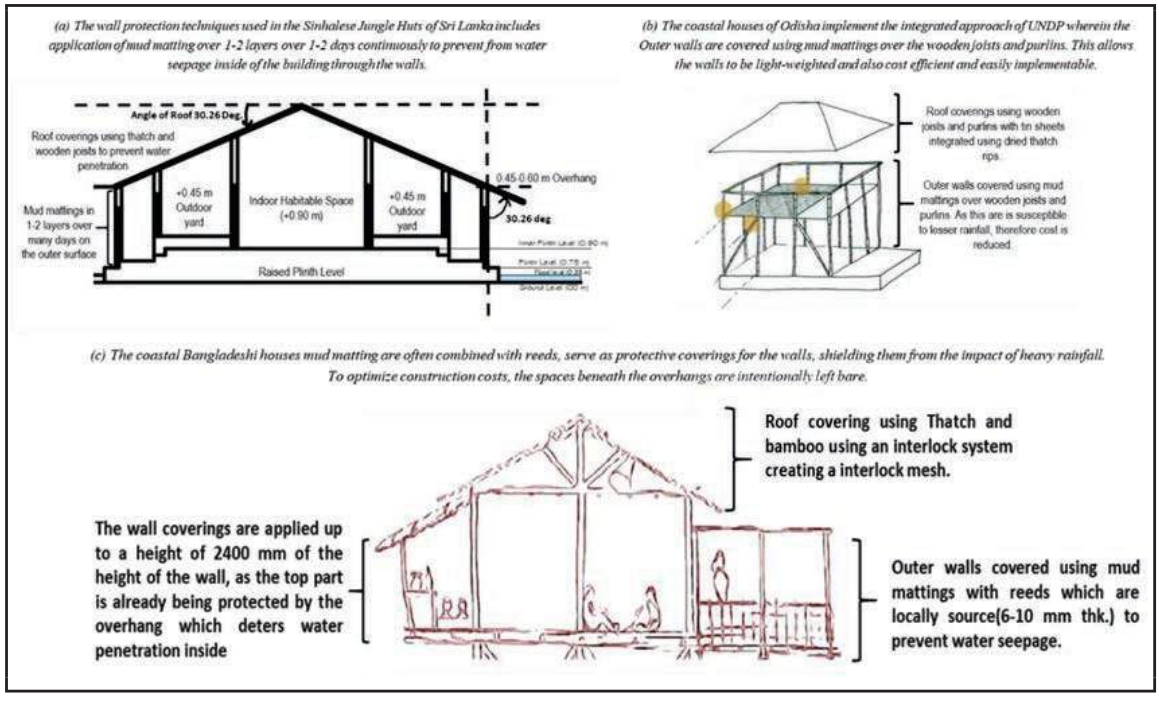

Fig. 3: Wall Protection Technique

Comparisons of the Features

The Sinhalese jungle huts in Northern Sri Lanka, houses in Odisha, India, and coastal houses in Bangladesh exhibit distinct architectural features shaped by their respective climatic conditions which is discussed in previous section. Coastal area of Bangladesh suffers from heavy rainfall and are susceptible to frequent flooding compared to Northern Sri Lanka and Odisha, India as discussed in Table 1. Northern Sri Lanka may experience floods, particularly during the monsoon seasons when heavy rainfall occurs. The region has faced challenges related to flooding rarely, especially during extreme weather events. Odisha is prone to floods, particularly during the monsoon season from June

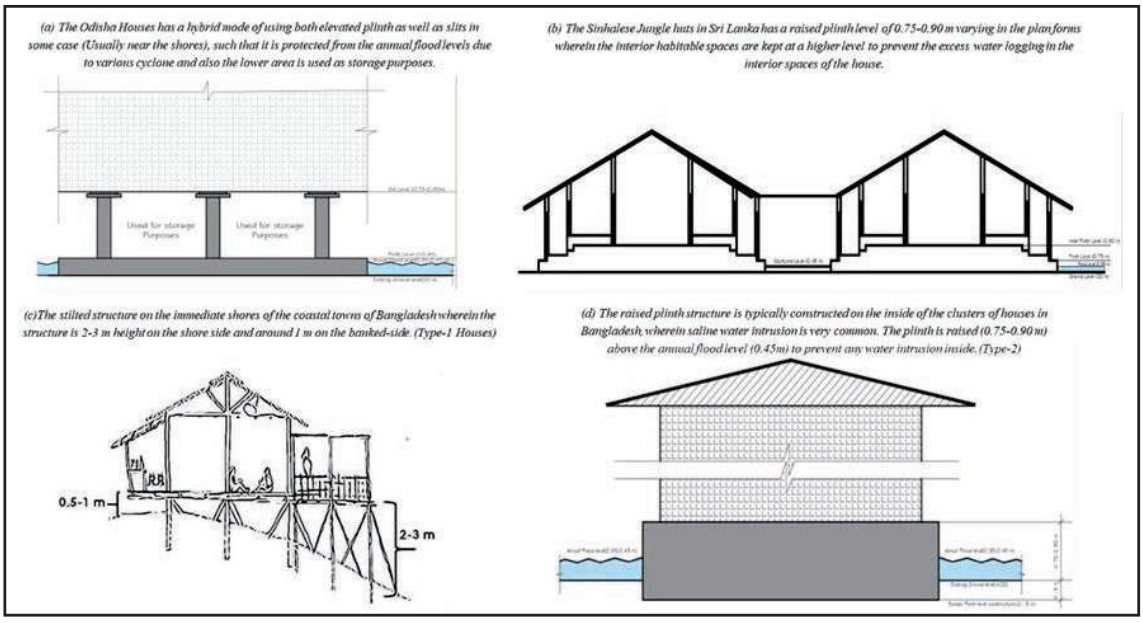

Fig. 4: Plinth Protection

to September. The state has a history of experiencing both riverine and coastal floods. Coastal areas of Bangladesh are susceptible to frequent flooding due to their low-lying topography and the influence of monsoons and cyclones. Riverine floods, storm surges, and tidal flooding are common occurrences. The frequency of floods in coastal Bangladesh is relatively high, and the region is prone to significant inundation during the monsoon and cyclone seasons.

The architectural differences, such as roof pitches, materials used, overhang lengths, wall protection techniques, and plinth protection, reflect the diverse approaches to housing influenced by the rate of rainfall and the frequency of flooding in each region. While Sinhalese jungle huts employ a roof with a 7/12 pitch and primarily use coconut thatch and bamboo for construction, Odisha houses showcase an 8/12 pitched roof integrated with wooden joists, purlins, and tin sheets. In contrast, coastal houses in Bangladesh feature a steeper 10/12 pitched roof with a unique interlock mesh of thatch and bamboo due to heavy rainfall in this region.

Overhang lengths vary, with the Sinhalese huts and Bangladesh houses ranging from 0.45-0.60 meters to 0.75-0.90 meters, while Odisha houses maintain a shorter overhang of 0.35-0.40 meters. Wall protection techniques also differ, with Sinhalese huts using layers of mud, Odisha houses employing mud matting over wooden structures, and Bangladesh houses incorporating mud matting with reeds. Plinth protection varies in terms of elevation and materials, reflecting the local preferences and environmental considerations of each region. These architectural disparities underscore the diverse approaches to housing influenced by rainfall rate and frequency of flooding.

Table 1: Comparative Assessment of Features Across Various Areas

Type of feature	Sinhalese jungle huts in Northern Sri Lanka	Odisha in India	Coastal Bangladesh Houses
Average annual rainfall*	1,000 to 2,500 millimetres	1,500 to 2,500 millimetres	1,500 to 3,000 millimetres or more
Angle of roof	7/12 , 30.26 degrees 58 % grade	8/12 , 33.69 degrees 66.67 % grade	10/12 , 42.26 degrees 88% grade
Roof materials	Predominantly using coconut thatch, dried coconut leaves and bamboo/mud for binding.	Wooden joists and purlins with tin sheets integrated using dried thatch rips.	Thatch and bamboo using an interlock system creating an interlock mesh.

(Table 1 Contd ....)

(.... Contd Table 1)

Overhang length	0.45-0.60 m while in some houses it is found to be around 0.75-0.90 m also.(1.5-2.0 ft usually).	0.35-0.40 m as this region faces a slightly lesser hazard of rainfall(1.0-1.5 ft usually).	0.45-0.60 m while in some houses it is found to be around 0.75-0.90 m also.(1.5-2.0 ft usually).
Wall Protection techniques	Mud in 2-3 layers over 1-2 days are applied.	Mud mattings over wooden purlins and joists	Mud mattings with reeds.
Plinth Protection	The structures features a raised plinth ranging from 0.75 to 0.90 meters, with bamboo walls adorned with mud matting. In certain instances, slits measuring 1 to 1.5 meters are incorporated, enhancing ventilation and aesthetic appeal.	The structures showcases a raised plinth, varying between 0.75 and 0.85 meters, complemented by wooden walls adorned with a combination of mud and bamboo matting. Additionally, coal-tar has been applied to the walls, contributing to both protection and preservation.	The foundation is elevated with a plinth height of 0.95 meters, employing bamboo uprights for the uplifting of the ground floor. The structure features bamboo walls embellished with mud matting, and strategically placed slits for enhanced ventilation and lighting.
* It's important to note that these are general estimates, and specific locations within each region may experience variations in rainfall patterns. Additionally, climate conditions can change over time, so it's advisable to refer to more recent meteorological data for accurate and up-to-date information on annual rainfall in these areas.			

INVESTIGATING THE IMPACT OF CYCLONE AND FLOODS ON THE ARCHITECTURAL FEATURES THROUGH THE LENS OF STANDARDS AND GUIDELINES

The correlation between design features in vernacular architecture and disaster resilience has prompted an examination of the guidelines outlined by the United Nations Development Programme (UNDP) (Chakraborty *et al.* 2021; Management, Programme, and India 2006). Notably, Odisha has wholeheartedly embraced these guidelines, leading to a substantial decrease in cyclone-related damages over time. Through a comparative assessment of disaster intensity, design elements, and UNDP guidelines, our study offers valuable insights for future architects and policymakers engaged in coastal area projects. The construction of millions of new houses under Odisha's rural housing scheme has proven instrumental in safeguarding the lives and livelihoods of impoverished and vulnerable communities. The success can be attributed to the implementation of principles such as transparency, technology, teamwork, timeliness, and transformation. The rural housing mission in Odisha operates under two government schemes—the Central Government-sponsored Prime Minister Rural Housing Scheme and the State Government's rural housing scheme. The government has enlisted the Central Building Research Institute (CSIR-CBRI) as a technical partner to provide suitable, appropriate, and disaster-resilient housing designs. The integration of transparency, technology, teamwork, timeliness, and transformation has yielded groundbreaking results.

To bolster the state government's efforts, UNDP has provided technical support for expediting the implementation of the rural housing program, introducing various technological solutions. For instance, the mobile app "Mo Ghar" facilitates the monitoring and evaluation of construction progress. The app, linked to the rural housing website, ensures that each instalment of the four-tranche fund is released only after the verification of construction progress through shared photographs. UNDP has also played a role in establishing management units, enhancing oversight capacity, and ensuring proper documentation. From April 2020 to March 2021, Odisha successfully constructed 438,747 houses, contributing to a total of 7.2 million houses since the project's inception. The Odisha government has fully embraced and implemented various features recommended by the UNDP along the coastal region villages to effectively mitigate damages caused by frequent cyclones. These include the incorporation of cyclone-resistant structures, elevated plinth levels in coastal towns, robust and durable foundations, wind-resistant designs, roof tie-downs, impact-resistant doors and windows, early warning systems, mangrove plantations, and active community engagement. The successful adoption of these measures was evident during Cyclone Fani in 2019, where Odisha emerged as the least affected state in terms of casualties and damages incurred.

In Sri Lanka, vernacular architecture, such as the Sinhalese jungle huts, has adapted over time to withstand natural disasters like cyclones and floods. While there is no singular national guideline specific to these huts, traditional construction practices align with broader disaster risk reduction frameworks supported by both national agencies and international bodies, such as the United Nations Development Programme (UNDP) and the Asian Disaster Preparedness Centre (ADPC) (Nissanka, Amaratunga, and

Haigh 2019; Patterns et al. 2006). The guidelines emphasize the use of locally sourced sustainable materials like coconut thatch, bamboo, and mud, which are readily available and effective in resisting wind and water damage. Furthermore, the Sri Lankan government has promoted Community-based Disaster Risk Management (CBDRM) programs that encourage the adoption of resilient construction techniques, such as elevated plinths and sloped roofs (Disaster Preparedness ECHO 2013). These practices are reinforced by traditional knowledge systems, which have been passed down through generations and adapted to the specific environmental conditions of the region. The integration of these community-driven guidelines into local construction practices has helped mitigate cyclone and flood impacts, as evidenced by reduced structural damage in recent cyclonic events. Such adaptations are supported by disaster management frameworks that prioritize decentralized and community-led approaches, aligning with global disaster risk reduction strategies such as the Sendai Framework for Disaster Risk Reduction.

In Bangladesh, where the frequency and intensity of cyclones and floods are among the highest in the world, there is a more structured approach to disaster-resilient construction, guided by the National Building Code of Bangladesh (BNBC) and supplemented by international recommendations, such as those from the UNDP and the World Bank (BNBC 2020; Management et al. 2006). The guidelines emphasize critical features like raised plinths, the use of light-weight materials (e.g., bamboo, thatch), and specific roof geometries to minimize wind-resistance. Additionally, the Comprehensive Disaster Management Programme (CDMP), a collaborative effort between the Government of Bangladesh and the UNDP, provides a framework for building cyclone-resistant houses (Luxbacher 2011). It promotes techniques such as reinforced walls, improved roofing materials, and elevated foundations, particularly in flood-prone areas. The CDMP also supports capacity-building initiatives at the community-level, ensuring that local populations are equipped with the knowledge and skills needed to construct and maintain disaster-resilient buildings. The success of these guidelines in reducing disaster impact is evident in the significant reduction of fatalities and property damage during recent cyclones like Cyclone Amphan in 2020. The coordinated efforts between local and international bodies have fostered a resilient architectural culture that integrates modern guidelines with traditional practices, ensuring sustainable and safe living environments.

According to the Government of India's notification on cyclone shelter management, cyclone shelters are structures designated for short-term use during natural hazard events such as cyclones, tsunamis, or floods. The sustainability of these shelters relies on their utilization and maintenance throughout the rest of the year when there are no ongoing natural hazards. Given the substantial investments in constructing cyclone shelters, it is considered wise to explore various other purposes that can contribute to maintaining these structures. There exists a difference of opinion among experts regarding the appropriate normal uses for these shelters. However, a consensus seems to favour uses that do not impede the primary function of the structure as a cyclone shelter. Design considerations should take into account local ethos and values to enhance the shelter's utility as lessons learned from Sri Lanka (Dayaratne 2018). Cyclone shelters are not just seen as a means of mitigation but also as agents of development, providing facilities for sustainable purposes like education and healthcare, thus contributing to local development. The guidelines emphasize features such as sustainable use, building specifications, accommodation capacity, location, shelter height, inner design, structural specifications, staircases, material selection, and their impact on structural considerations. It is acknowledged that heavy cyclones can inundate large areas, potentially requiring helicopters for access to affected regions. The terraces of cyclone shelters may serve as landing spaces for helicopters due to their elevated and sturdy nature. Design parameters must be determined, and cost implications need to be considered to address the dynamic forces generated during helicopter landing and take-off on the structural integrity of the shelter.

CONCLUSION

This study delved into the assessment of disaster impact on the shaping of vernacular architecture in coastal areas, focusing on three case regions along the western ring of the Bay of Bengal: Sinhalese jungle huts in Northern Sri Lanka, houses in Odisha, India, and coastal houses in Bangladesh. The research specifically examined the influence of rainfall and flooding on architectural design by conducting a comparative assessment of various features, including roof pitches, materials, overhang lengths, wall protection techniques, and plinth protection. The findings revealed that architectural design features vary across coastal regions based on the intensity of rainfall and the frequency of flooding. Vernacular architecture, characterized by the use of locally sourced materials and evolved construction techniques, has demonstrated its effectiveness in responding to environmental challenges. Recognizing the dynamic relationship between design features, disasters,

and international guidelines, architects and policymakers can develop resilient built environments in coastal regions. This research serves as a foundation for further exploration in other coastal areas, contributing to a more holistic understanding of disaster-resilient architectural practices.

CONFLICTS OF INTEREST

No conflict of interest was declared by the authors.

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Determination of Geotechnical Properties of Soil and Disaster Vulnerability Analysis

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Abstract—This research aims to understand the factors and processes contributing to landslides by determining the geotechnical properties of soils and conducting numerical analyses of slope failures along the state highway in the eastern part of Mizoram, where Melbuk village is situated uphill of the study sites. This study employed geotechnical approaches and numerical analyses to determine the factor of safety. Due to toe-cutting for the construction and widening of the road, landslides triggered by rainfall occurred. Two landslides, at location 1 and location 2, were investigated where slope failure occurred down slope of Melbuk village. The stability of the slopes and probable landslide mechanisms were determined using various techniques, including limit equilibrium techniques, which evaluate the driving and resisting force equilibrium along possible failure surfaces. The Limit Equilibrium Method is extensively used in geotechnical engineering to assess slope stability and suggest remedial measures. From the Atterberg limit of the soil, it is observed that location 1 soil has silty-clay soil and location 2 has silt soil. The laboratory analysis of soil obtained by direct shear test concluded that the cohesion and angle of friction for location 1 is greater than location 2, indicating that location 1 has higher stability. The stability of the slopes was analyzed, and the factor of safety obtained by different methods is 0.827 and 0.719, respectively. Both the study sites has factor of safety less than 1, indicating an unstable slopes which are highly vulnerable to sliding. A debris slide is observed at both study sites. Hence, remedial measures are suggested based on the research findings.

Keywords: Slope stability, Limit Equilibrium Method, Atterberg Limit, Plastic Limit, Liquid Limit

INTRODUCTION

A landslide is the rapid movement of the earth's material down a slope, which may be composed of soil, rock, vegetation, or debris, or a combination of all, under the influence of gravity with triggering factors that can be natural, anthropogenic, or both (Cruden and Vernes, 1996; Nemcok *et al.*, 1972; Vernes, 1954; Geertsema *et al.*, 2009; Anbalagan *et al.* 2015; Turner, 2018). A stable slope is a condition where all the slope-forming materials remain unchanged and exhibit no displacement (Varnes,1978; Choubey, 1992). If the shear strength of the soil is adequate to counteract this tendency, the hill slope remains stable; otherwise, a slide occurs (Tiwari and Ajmera, 2023).The rate of movement of different landslide types is highly variable. Slides move relatively slowly in comparison to flows (Cruden and Varnes, 1996). The rate of movement during slope failure depends on the nature of the slope-forming material and the shape of the slip surface (Evans *et al.*,2006; Gajamer and Kumar, 2023; Asthana and Sah, 2007;). When ground stress exceeds the strain at which peak ground strength occurs, significant acceleration of movement may happen on slopes made of brittle materials (Nichol *et al.*, 2011). Other materials, particularly sensitive or fast clays,

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lose almost all of their strength when remoulded, leading to extraordinarily fast movement rates.

The risk of a landslide is calculated using landslide risk analysis, considering the risk to people, communities, assets, or the environment (Guillard-Gonçalves *et al.*,2016). Both the magnitude and speed of landslides can vary, occurring either slowly and gradually or quickly and catastrophically (Alcana-Ayala, 2023; Clague 2013). There are several possible causes of landslides, including prolonged periods of intense rainfall, seismic activity, volcanic eruptions, construction or deforestation, and natural phenomena such as soil erosion or unstable slopes (Turner, 2018). Landslides not only represent a major risk to human life and safety but can also seriously harm houses, infrastructures, and the environment (Turner, 2018). Reducing the effects of landslides on communities and ecosystems requires the use of prevention and mitigation techniques, including appropriate land use planning, slope stabilization techniques, and early warning systems (Turner, 2018).

Landslides are investigated and evaluated in geotechnical engineering using various methodologies to comprehend their causes, forecast their occurrences, and lessen their effects (Coutinho *et al.*, 2019; Lasker and Pal, 2012; Safari *et al.*, 2019). Determining possible landslide-prone zones requires an understanding of the geology and geomorphology (Sanei *et al.*, 2015; Bland and Rolls, 2016; Huat *et al.*, 2012). To ascertain the vulnerability and risk of landslides, geologists examine geological structures, rock types, slope aspects, and landforms. Geotechnical parameters, including the Atterberg limit, shear strength, permeability, and compaction, help identify the engineering characteristics of soil and rock (Sanei *et al.*, 2015; Abbas *et al.*, 2017).

Mizoram and the other states of northeastern India are characterized by rough, mountainous terrain with young topography (Nandy *et al.*, 1983). The collision between Indian and Burmese plates formed an intercalated succession of argillaceous and arenaceous deposits, characterized by a Cenozoic sedimentary succession. Predominant rocks originating from the Tertiary period include sandstone and shales, which are representative of ancient shallow marine settings (Nandy *et al.*, 1983). Most of the rock formations trend north-south due to tectonic plate collisions, with the older Barail group rocks found in the eastern portion of the state. The Barail group of rocks is distinguished by discrete siltstone and silty-shale disseminated across very-fine to fine-grained sandstone (Alam, 1991).The entire sedimentary columns of Mizoram consists of an alternating sequence of argillaceous and arenaceous rocks, comprising sandstone, silty-sandstone, mudstone, shale, shaly-sandstone, silty-shale, and their admixture in various proportions(Karunakaran, 1974;Ganju, 1975; Tiwari, 2014). Additionally, there are occasional intra-formational conglomeratic bands and pockets of shell limestone.

Landslides are prevalent, destroying properties, causing loss of life, and economic disruption, particularly in settlement areas and along roads and highways (Mc Coll, 2022). The majority of landslides in Mizoram are triggered by rainfall and human activities (Dinpuia, 2019).The design of a stable slope angle, where deep cuts are involved, is rarely based on stability analysis (Dinpuia, 2019; Kumar *et al.*, 2022). A lack of awareness about the characteristics of the slope, the materials that comprise the hill, and other pertinent elements is the primary cause of most landslide hazards (Alcantara-Ayala and Sassa, 2023). However, with proper planning, these issues can be mitigated, and appropriate precautions can be taken as needed to maintain slope stability (Alcantara *et al.*, 2023; Rovins *et al.*, 2015). The stability of the slopes, and the risk, and vulnerability of landslides are examined using various techniques, including the limit equilibrium method, which evaluates the equilibrium of driving and resisting forces along possible failure surfaces (Duncan, 1996; Dinpuia, 2019).

Anthropogenic activities, including road construction, habitation, and other slope-management-related activities, are the main causes of landslides in mountainous regions. Studying the properties of the soil and rock mass is crucial (Misbahudin, 2020). A scientific study of the geotechnical properties of soil helps us understand the nature of topography and can lead to solid suggestions for mitigating and preventing potential hazards.

The study area (Figure 1) is in the north-eastern part of Mizoram, near the Indo- Myanmar border. The state highway from Champhai town to Zokhawthar village is an important route near the Indo-Myanmar border andserves as a hub for trade and commerce. Various commodities are traded in its lively marketplaces, which are well-known.

Zokhawthar village benefits from its proximity to Champhai town due to its location near the international border with Myanmar. Its significance lies in facilitating trade, offering necessities, promoting cross-cultural interaction, and acting as a transportation centre, all of which support the socio-economic growth and general well-being of the neighbouring districts.

Champhai to Zokhawthar highway has been upgraded from a single-lane state highway standard to a two-lane national highway standard. Following its completion in August

2021, heavy rainfall triggered multiple landslides along the route, rendered it inaccessible in November 2021. This route passes through several villages, including Melbuk. The settlement of Melbuk village is on the upslope of the road, which is 11 kilometers from Champhai town, and is home to 292 families.

Two landslides located at location 1 (23°23'34.00"N; 93°22'42.00"E) and location 2 (23°23'43.00"N; 93°23'18.00"E) have been observed at the toe of Melbuk village along Zokhawthar road. These massive landslides have affected the village community, making five residential houses and one church vulnerable to collapse. The landslides are active rotational slips, causing damage to the newly constructed highway by heavy load exerted by the upslope debris. It has been observed that location 1 has subsided by 6 feet. For this reason, understanding the risks associated with landslides is crucial for safety, risk mitigation, and the security of life. To lessen the environmental impact, the communities can regulate land usage more effectively and implement conservation measures.

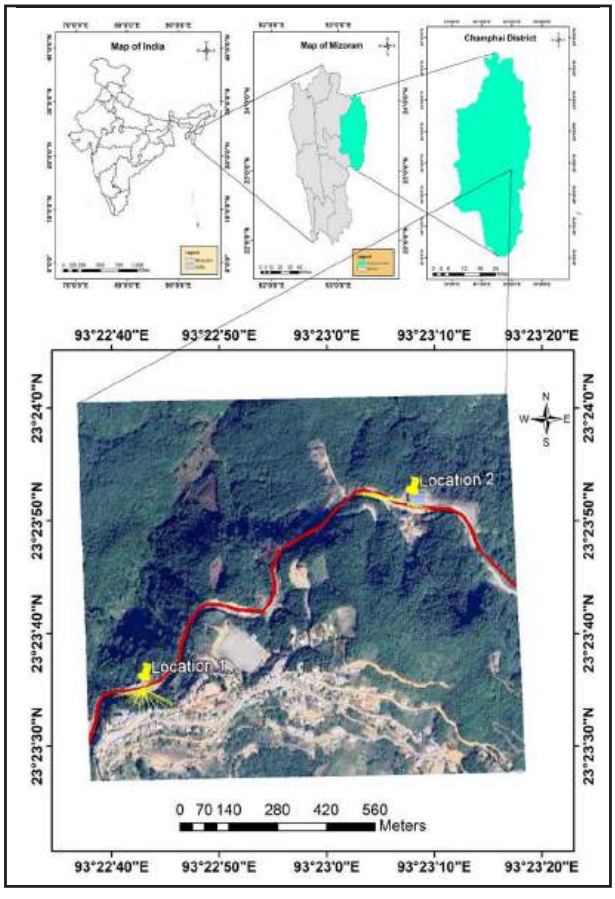

Fig. 1: Location Map of Study Area

MATERIALS AND METHODS

Field Investigations

Field investigations were carried out in the study area to identify probable slope instability variables, such as topography, geology, vegetation, drainage patterns, and landslide evidence, by conducting thorough visual investigations of the sites. Soil samples were collected from the field and tested in the laboratory, where the Atterberg limits and direct shear of the soil were determined (Atterberg, 1911). Detail flowchart depicting methodology is shown in figure 2.

Atterberg Limit

The Atterberg limit is a basic measure of the critical water content levels under different external forces. Liquid limit (LL), plastic limit (PL), and shrinkage limit (SL) are the three primary parameters (Atterberg, 1911). Using the Casagrande apparatus, the liquid limit of the fine-grained soil is determined. The soil sample is combined with water to form slurry. The liquid limit is the moisture content at which the soil transitions from a semi-solid to a liquid state (Casagrande, 1948).

Plastic limit (PL) is the moisture content of soil upon rolling on a flat glass plate until it crumbles (Atterberg, 1911; Casagrande, 1948). Water is added to the soil gradually until it achieves the plastic condition (Atterberg, 1911; Casagrande, 1948). The plastic limit is the water content at which the soil may be spun into a 3.2 mm diameter thread without collapsing.

Plasticity index is used in geotechnical engineering to evaluate the plasticity of fine-grained soils, such as clay or silt(Casagrande, 1932; Roy and Bhalla, 2017). It is an essential parameter for understanding the behaviour of soils. It is obtained by subtracting the value of liquid limit to plastic limit of soil. The greater plasticity in the soil is indicated by higher plasticity index, which suggest that variations in moisture content will result in the soil varying in volume and consistency more significantly (Atterberg, 1911; Casagrande,1932 &1948). Soil with high plasticity index is highly compressible; a high value of the plasticity index indicates a high degree of cohesiveness. High plasticity index soils are typically clay-dominated, whereas low plasticity index soils are typically silt-dominated.

Direct Shear Test

The direct shear test is a common laboratory experiment performed to determine the shear strength parameters of

soil (Karsten *et al.*, 2006; Sanei *et al.*, 2015). It is particularly usedto assess the behaviour of cohesive soils like clays and silts. To assess the shear strength of the soil, a controlled shear force is applied to a sample of soil.

Limit Equilibrium Method (LEM)

The Limit Equilibrium Method (LEM) is a method that is extensively used in geotechnical engineering to assess slope stability and its remedial approach (Duncan, 1996). The basic principle is the idea of maintaining the balance between the internal resistive forces supplied by the soil or rock mass and the external forces operating on a slope or structure. The equilibrium conditions are imposed at critical points along the possible failure surfaces because the limit equilibrium technique holds that the structure has the potential to fail. To maintain stability, this usually entails analysing forces and moments in both the vertical and horizontal orientations. An essential parameter in slope stability analysis is the factor of safety, which is the ratio of driving forces to resisting forces. A stable slope is indicated by a factor of safety more than 1, and possible instability is indicated by a factor of safety less than 1 (Duncan, 1996).

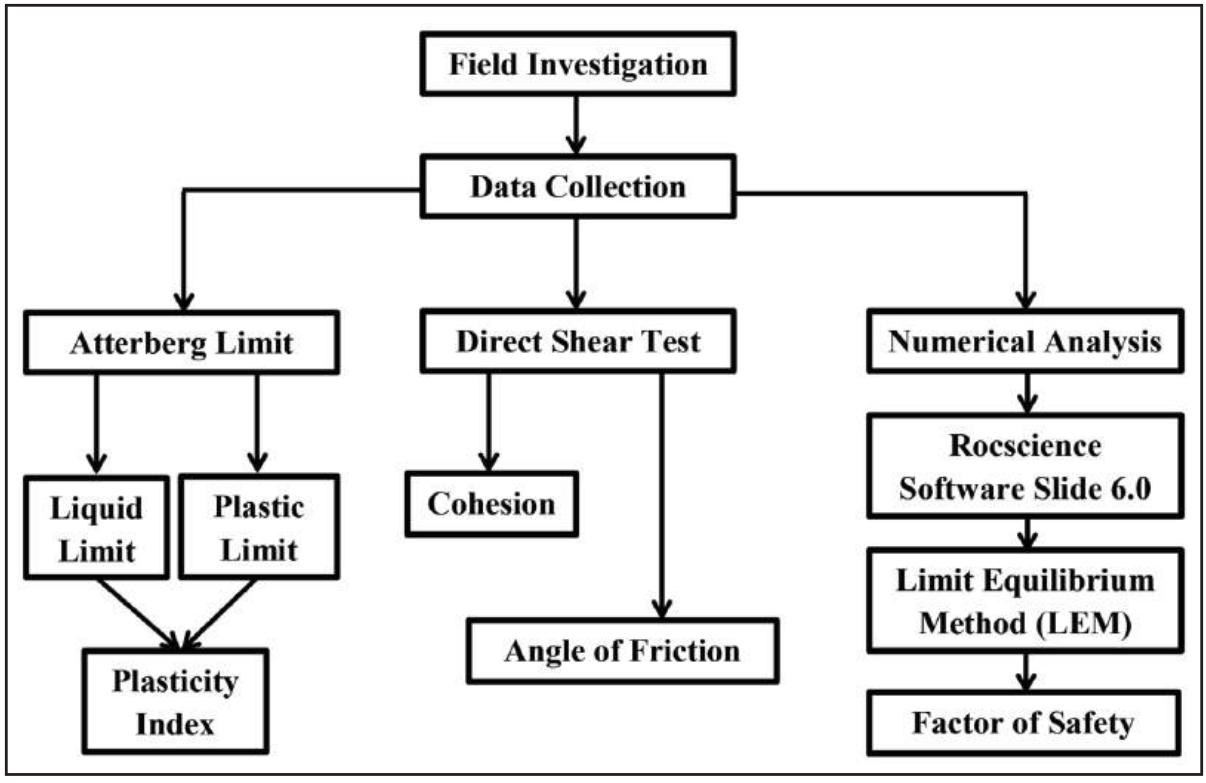

Fig. 2: Flowchart Depicting Methodology

RESULTS AND DISCUSSION

Field photographs (figure3) depict visual documentation of the study sites, where soil samples, geometry, and geology of the field were observed. The coordinates of the study sites were positioned using a differential global positioning system (DGPS).

Determination of Atterberg Limit

Atterberg limits are used to categorize and describe the behaviour of fine-grained soils according to the changes in moisture content that cause the soils to become liquid, plastic, or semi-solid. The Atterberg limit was performed on fine-grained soil, as per Indian Standard IS: 2720 (Part 5)-1985, in order to determine the critical water content. The detailed laboratory observation is given in table 1. The plasticity index of the soil is obtained by the numerical difference between the liquid limit and the plastic limit, where these three parameters, i.e., liquid limit, plastic limit and plasticity index constitute the Atterberg limit. It is used to assess and classify the plasticity and behaviour of fine-grained soils for various construction and soil-related applications.

Fig. 3: Field Photographs: (a) Location 1, (b) Location 2

Liquid Limit

The liquid limit is the minimum water concentration at which soil begins to behave like a liquid. For determining the liquid limit, a 200-gram sample of oven-dried soil that passes through a 425 µm sieve is obtained. The liquid limit test is conducted using the Casagrande method, and the results are recorded based on the number of required blows for the soil to close a groove of a specific length (Casagrane, 1948). The liquid limits for location 1 and location 2 are 20.32 and 20.29respectively. Therefore, the soil of location 2 tends to lose its strength and fail more rapidly at low water content than the soil of location 1.

Plastic Limit

The plastic limit is the water concentration of fine-grained soil below which it loses its plastic properties. As per IS: 2720 (Part 5)-1985, the plastic limit test is performed. The soil is rolled into thin threads around 3 mm in diameter, and begins to crumble. The plastic limit of the soil test was done for 4 trials. The plastic limits for location 1 and location 2 are 19.66 and 17.62 respectively. Since, soil lose its cohesion below their plastic limit, the soil in location 1 has more ability to remain cohesive than location 2.

Plasticity Index

It is a metric used to a13 the soil type is silt. It shows the variation between the liquid limit (LL) and plastic limit (PL) of the soil. It is calculated by obtaining the difference between the liquid limit and the plastic limit (ASTM, 2010). The plastic limits for location 1 and location 2 are 9.54 and 2.67 respectively. Since, soil with a higher plasticity index has a greater potential for changing its volume, therefore, the soil of location 1 possess more ability to change its volume. Based on the plasticity index, location 1 is classified as medium plastic and has a silty-clay soil. Location 2 is classified as slightly plastic and the soil type is silt.

Table 1: Atterberg Limit Values of location 1 and Location 2

Parameters	Location 1	Location 2
Liquid Limit	20.32	20.29
Plastic Limit	19.66	17.62
Plasticity Index	9.54	2.67
Type of Soil	Silty-Clay	Silt

Direct Shear Test

As per IS: 2720 – 13(1986), this test is used for determining the shear strength of the soil samples. As shown in table 2, the angle of friction obtained for location 1and location 2are 21.29°and 17.84° respectively. Therefore, with a higher angle of friction in location 1, it possesses greater resistance to shear deformation under applied stress. The normal stress versus shear stress of direct shear test is shown in figure 4 and 5.

The cohesion obtained (table 2) for location 1 and location 2 is 26.4 kN/m2 and 14.22 kN/m2 respectively. Since, a higher cohesion of soil implies stronger internal bonding forces between particles, it increases resistance to shear stress and stability. Therefore, location 1 has higher stability and resistance to shear stress.

Limit Equilibrium Method (LEM)

Melbuk Village lies uphill of study sites and the route that connects it to Zokhawthar passes through the downhill of the village. The two locations were analysed using Rocscience software LEM 6.0 (figure 6 and figure 7), and the factor of safety for the two locations wasdetermined. Based on the parameters obtained from the direct sheartest; i.e., cohesion and angle of friction, the slope stability wasanalysed for location 1 and location 2 (table 3).The community has been impacted by these landslides, placing one church and five residential homes at risk of collapsing. It has been observed that location 1 has sunk to a depth of six feet (Figure 6).

Location 1 is an active debris slide caused by large-scale cut slope failure at the toe, comprising a reasonably thick overburden, mostly loose debris. The unchannelized water of domestic waste that penetrated the dense overburden decreased the cohesion of the soil. At the base of the landslide, gabion walls were built without the use of slope-easing techniques. A rotational sliding caused the asphalt to bubble up, causing damage to the road and some of the gabion walls. The impacted region measured roughly 62.2 meters in length and 100 meters in width. The average factor of safety of location 1 for different methods is 0.827.

Location 2 is also an active debris slide due to cut-slope failure at the toe, where unconsolidated earth material moves rapidly down the slope. These cut slope were for the construction of state highway connecting Champhai to Zokhawthar village. A gabion walls at the toe were damaged by landslide debris. The unchannelized widespread flow of water including surface runoff and those penetrating the ground contributes as one of the triggering factors for location 2 slope failure. The sliding area stretched about 189 meters in width and 69.57 meters in length. The average factor of safety for different methods is 0.719.

Table 2: Shear Strength Parameters

Location	Sl. No.	Normal Stress σ (kg/cm²)	Shear Stress at failure τ (kg/cm²)	Cohesion (c) (kN/m²)	Angle of Internal Friction (Φ)
1	**1.**	0.5	0.686	26.4	21.29°
	2.	1	1.151		
	3.	1.5	1.538		
2	**1.**	0.5	0.293	14.22	17.84°
	2.	1	0.495		
	3.	1.5	0.615		

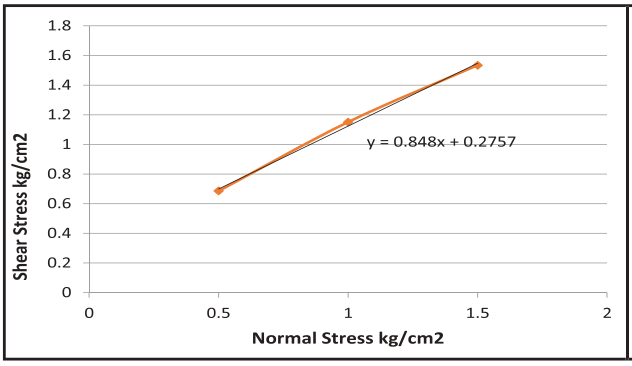

Fig. 4: Normal Stress *Vs.* Shear Stress for Location 1

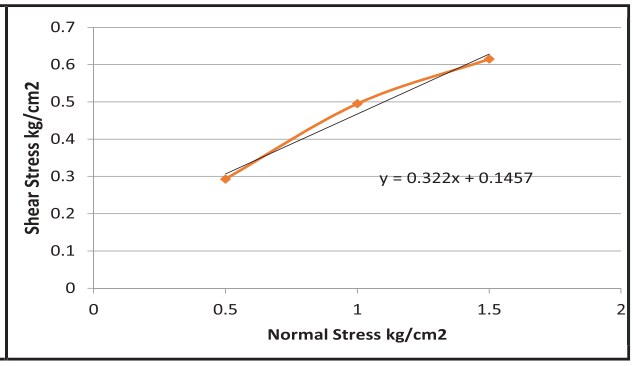

Fig. 5: Normal Stress *Vs.* Shear Stress for Location 2

Fig. 6: Subsidence of Slope and Upward Movement at the Highway

The slope stability analysis using the Limit Equilibrium Method based on the Mohr-Coulomb criterion indicates that the factor of safety obtained through various methods for study sites location 1 and location 2 are less than 1, respectively. It can be understood that the forces exerted by gravity and pore water pressure, which tend to cause slope failure, are greater than the resisting forces of the rock and soil. The stress is below the permissible limit, and slope failure is very likely to occur. Consequently, the slope is vulnerable to failure under saturated conditions.

Table 3: Factor of Safety Analysed by LEM

Method	Location 1	Location 2
GLE/ Morgenstern-Price	0.849	0.74
Janbu Simplified	0.797	0.691
Ordinary/ Fellenius	0.807	0.7
Bishop Simplified	0.857	0.745

CONCLUSION

In this study, the slope stability of the two locations was analysed using Rocscience Software Slide 6.0. From the laboratory analysis, the Atterberg limits concluded that the soil type for location 1 and location 2 is silty-clay and silt, respectively. From the liquid limit and plastic limit, the plasticity index was calculated, with 9.54 for location 1 and 2.67 for location 2. The direct shear test concluded that the soil in location 1 has higher values of cohesion and angle of friction, indicating that the soil possesses more shear strength and stability. The high-angle slopes comprise poor rock mass covered by loose, thick soil, requiring mitigation measures to stabilize the area. The active rotational sliding made the upslope highly vulnerable. Therefore, during the monsoon, excess runoff and percolation may reduce the cohesiveness of the soil, increasing pore pressures and lessening the resisting force, which can act as a triggering factor for slope failure.

Based on the investigations and findings, mitigation strategies are recommended to lessen the risk of hazards and enhance slope stability while also minimizing susceptibility. The generalized measures for slope stability include modifying the high-angle slope by adding a reinforced terrace (benches ≤ 3 m) that slopes from the crown, which can lessen the driving force of the slopes. The kinetic and translational energies of soil will decrease if the slope angle is changed to a milder one.

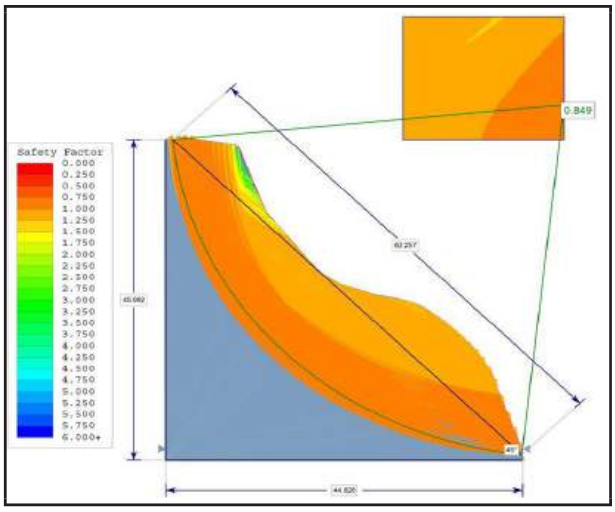

Fig. 7: Slope Stability Analysis using Limit Equilibrium Method for Location 1

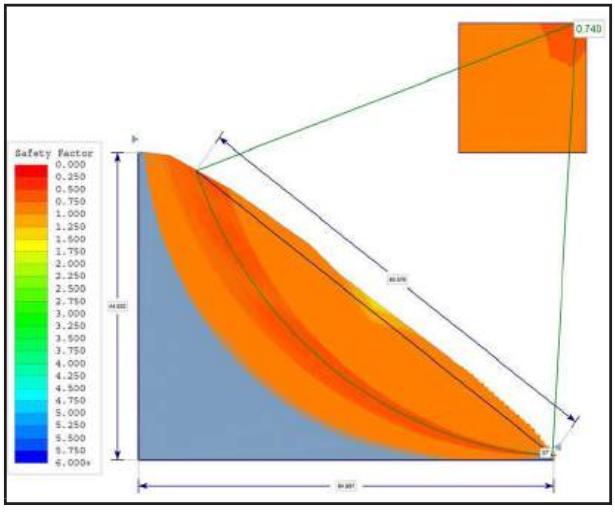

Fig. 8: Slope Stability Analysis using Limit Equilibrium Method for Location 2

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Identifying the effect of Success Factors on Predicting Android Mobile App Success on Google Play Store

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Abstract—At the present time, mobile apps play an imperative role in everyone's life. Thousands of apps are being put on the Play Store market for users to install every day. But the life of the app on the Play Store depends on its success parameters. As there is substantial growth in the mobile app market, the competition among software app developers has also increased. Several attributes of an app, attributes that are either internal or external to it, can perform a substantial role in deciding whether the app will be successful or not. In this research paper, an effort has been made to find the success factors that may affect the success of the app. For this, a literature survey is first conducted to find these success factors, and then a survey is conducted through an online questionnaire from mobile app users. Findings from the survey corroborate that out of 14 identified success factors, the security of on app plays a pivotal role. After that, design quality and content quality equally play another major role in the success of an app. The mobile app reviews/input collected via the survey are further utilized as influencers/predictors in predicting the overall success of an app using Machine learning algorithms. To achieve this, various Machine Learning algorithms are applied using "Python web-based interactive Jupiter Notebook 7.0.8". The accuracy of the final selected model is 96%, which is the highest accuracy among many existing models in the literature.

Keywords: Mobile Applications, Prediction, Android, success, failure, survey, Machine Learning.

INTRODUCTION

The use of mobile technology has boomed all over the world in the last 20 years. As the demand for mobile devices has drastically increased in the last two decades, the mobile app development and deployment on respective app stores of mobile device has also amplified. Unlike many other mobile OS, Android apps play a major role in the mobile software industry. Google Play Store on Android mobile devices provides access to millions of apps to work on. Daily, this platform is flooded with an enormous number of fresh apps. Developers of these apps are in anticipation that their hard work should not be in vain and try to build an app that will be successful in this competitive market. It would be beneficial for the developers to know in advance if their app will be successful or not before uploading it to the Google Play Store. It would prove to be highly advantageous for developers to have a method that can aid in predicting the success possibility of an application.

The success of an app can be ascertained by features like ratings, number of installs, and reviews rather than the revenue it generates. Generally, many apps in the Play Store are not charged; the revenue generated by subscriptions, in-app purchases, and in-app advertisements is practically unknown. Although many apps are added to the Play Store daily, only a few apps achieve their monetary benefits and

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endure in their respective competitive marketplaces. It would be really helpful if the possibility of app success could be ascertained in advance.

This paper is divided into four sections. After the introduction in section 1, the methodology adopted in this paper is presented in section 2. Then in section 3, the entire process of forming the Research Questions (RQs), the method adopted for answering the formed RQs, and finally, the results of the RQs are presented. Section 4 presents the conclusion and future work.

MATERIAL AND METHODS

The analysis of the survey starts with defining the Research Questions and the elaboration conduct of the online survey.

Defining Research Questions and Conducting the Survey

The goal of this research is to help developers understand and predict the app's success on the Play Store. In reaching this final goal, first, there is a need to identify what forms the basis. In light of this, three Research Questions (RQs) are formed:

RQ1. What are the different mobile app success factors?

RQ2. Can success factors affect the mobile app success prediction process?

RQ3. Is there a way/model to predict an app's success on the Google Play Store using Machine Learning Algorithms?

The answer to the first RQ is achieved through a literature survey from existing sources. RQ2 is further answered with the help of an online survey. For conducting the survey Google form was created, and a total of 09 questions were designed to be asked in 2-3 minutes. The questionnaire is forwarded as a Google form link https://forms.gle/ke9DK66LTuwwtCVK9 through various social media messaging systems to around 1200 users as a volunteer from 3.07.2024 to 3.10.2024. The response rate was 67 percent. The questionnaire is added in Appendix A. For accomplishing RQ3, various Machine Learning algorithms are used. Data sets for experimental analysis are collected from various sources (mostly mobile app developers and freelancers).

RESULTS REPORTING

The results for RQ1, RQ2, and RQ3 are presented in this section.

Answering RQ1

After a thorough review of existing research in the literature, some of the success factors were identified for investigation under this research, thus answering RQ1: -

1. ***Subjective Norms:*** The intent to use mobile apps can be influenced by the opinions of one's friends, and the adherence to social norms can also impact this decision [1], [2], [3], [4], [5], [6].
2. ***Perceived Compatibility:*** Compatibility measures the level of conformity between newly released products [1], [3], [7], [8], [9].
3. ***Perceived Playfulness:*** The notion of perceived playfulness pertains to the interaction between users and information systems, stemming from their focus, inquisitiveness, and delight.[1], [10], [11], [12], [13].
4. ***Satisfaction:*** Satisfaction is obtained through practical application, which ultimately influences the users' intention to continue. [1], [8], [9], [14], [15].
5. ***Perceived Usefulness:*** This refers to the extent to which an individual perceives that the utilization of a specific product or system will improve their job performance [1], [11], [13], [14], [16], [17], [18], [19].
6. ***Perceived Ease of Use:*** This is the extent to which an individual perceives that utilizing a specific product or system will be uncomplicated. [1], [10], [13], [17], [20], [21].
7. ***Content Quality:*** Quality of data supplied by Apps [22], [23], [24], [25].
8. ***Reliability:*** Refers to App crashes or any other cause for an app not working as anticipated [9], [19], [22], [26].
9. ***Security:*** It deals with probable harm to personal data, protection, possible disclosure to deceit, and malicious action on the web [18], [22], [26], [27], [28].
10. ***Design Quality:*** It refers to the user interface, i.e., what users, when they are engaging with your app, see, touch, and experience on their phone [9], [13], [22].
11. ***Usefulness:*** Professed usefulness of the app, its functionality, and services [18], [19], [22], [29], [30], [31].
12. ***Performance:*** It indicates how the app is functioning and how responsive the app is to the end-user [18], [22], [30], [31], [32].
13. ***Social Media integration:*** Allows users to easily share content with their friends on social networks [9], [13], [33].
14. ***Regularly updated:*** It means there is a certain system of mobile app updates that arise out of necessity, such as bug fixing, new feature releases, and so on [9].

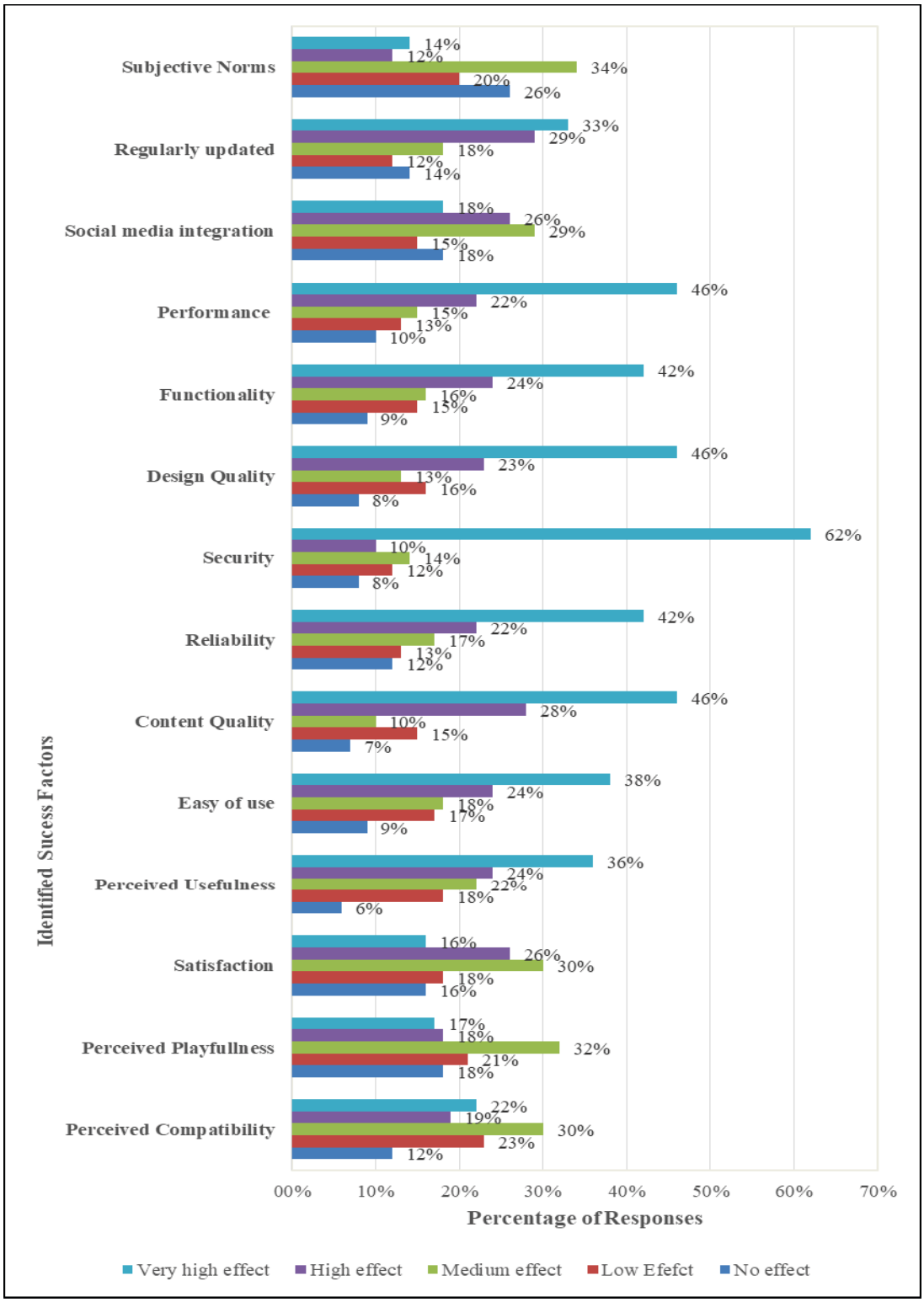

Fig 1: Influence of Success Factors on Mobile App Success on the Play Store by Respondents

Answering RQ2

The answer to RQ1 forms the basis for getting an answer to RQ2. The goal of the online survey is to identify the impact of various identified success factors on success prediction. The target audience of this survey is actual users of the mobile app. Figure 1 presents the influence of success factors on mobile app success in the Play Store by respondents from "No Effect" to "Very High Effect".

The fourteen success attributes/factors identified from the existing literature are further investigated by mobile app users via an online survey. The extent of influence of success factors on mobile app success prediction is collected on a 5-point Likert scale from "No Effect" to "Very high Effect". The result of these responses is further used for deriving weights using weighted average, which is popular and applied in many studies. [34], [35][36]. The formula for the weighted average is shown in Eq. (1).

$$W_j = \frac{\sum_{k=0}^{4}(x * w_k)}{N} \quad (1)$$

Where W_j notes weight assigned to the jth success factor.

w_k is the rating assigned to jth success factor in the range 0 to 4, signifying no effect, low, medium, high, and very high effect. x is the no. of responses for a w_k and N is the total number of responses. The weighted average values for each success factor using eq. (1) are shown in Table 1. The motive behind identifying the success factors and their influence on the success of the app on the Play Store is to assist in the further understanding of how these factors can impact in predicting the success using a prediction algorithm. It This also be noted that the existing research studies on success prediction methods for mobile apps do on incorporate the influence of the identified 14 success factors. The author believes that this research gap can further be investigated by implementing them in prediction methods and analyzing the results.

Table 1: Success Factors with Assigned Weights

Sr. No.	Success factor	Assigned weights
1.	Subjective Norms	1.69
2.	Perceived Compatibility	2.15
3.	Perceived Playfulness	1.95
4.	Satisfaction	2.07
5.	Perceived Usefulness	2.62
6.	Perceived Ease of Use	2.61
7.	Content Quality	2.85
8.	Reliability	2.65
9.	Security	3
10.	Design Quality	2.78
11.	Usefulness	2.70
12.	Performance	2.76
13.	Social Media Integration	2.10
14.	Regularly updated	2.51

Answering RQ3

1. Data Collection

In this research work, a mobile app dataset is collected from three freelancing mobile app developers. The data providers kept account of the limited variables/features of the mobile app. However, after approaching them for the required data (to consider 14 success factors while developing the app) as per our studies, they were able to keep and share the data. The dataset had 21 columns and 230 rows (200 after removing outliers). The variables such as App Name, Category, LOC, APK Size, Avg Rating, Installs, Version, and Free/Paid are already kept by the developers. The rest of the variables identified as success factors by the author are also accounted for as requested. Each of the success factors is given a score by the developer based on the guidelines in Table 2.

2. Data Cleaning

The dataset initially had 230 rows (mobile apps). The duplicate, missing, and inappropriate rows were removed and leaving 200 rows. The valid data is selected, and the garbage values are cleaned from the dataset collected from the developers. Relevant features or attributes required for success prediction are chosen.

3. Data Pre-processing and Data Selection

Data is prepared for classification to enhance classifier accuracy, and the Avg Rating column is chosen as the target variable for success prediction. The following are the preprocessing tasks performed on the data to prepare for classification models: -

- Casting of Installs to int, Avg. Rating and Price to float (and remove $ from Price column).
  Encode features (Type, Category) by label encoding method.
- Replaced the Size column with unified size values by converting Megabytes and Kilobytes into Bytes, then normalizing App size values.
- Remove unimportant features like (App Name, Version, and Last update).

Table 2: Guidelines for Developers for Scoring the App Success Factors

Sr. No.	Variable	Description	Categories	Score
1.	App Name	Name of the App		None
2.	Category	Category of the app		None
3.	LOC	Line of Code for each app	Numeric	None
4.	APK Size	Size of an App in terms of MB	Numeric	None
5.	Avg Rating	App Avg rating on the Play Store	Numeric	None
6.	Installs	No. of downloads	Numeric	None
7.	Version	Android Version supported by the app	Numeric	None
8.	Free/Paid	If the app is free on the Play Store or not	Yes	1
			No	0
9.	Subjective Norms	Was the app sponsored or recommended	Yes	1
			No	0
10.	Perceived compatibility	Installing the new version of an app on an older version	Yes	1
			No	0
11.	Perceived Playfulness	Does the app pertain to the users stemming from their focus, inquisitiveness, and delight?	Yes	1
			No	0
12.	Satisfaction	Is the user willing, after being fully satisfied, to continuously use the app in the future	Yes	1
			No	0
13.	Perceived Usefulness	Does the app improve users' job performance	Yes	1
			No	0
14.	Perceived ease of use	Whether the usage of the app is easy or not	No	0
			Yes	1
15.	Content Quality	If the user is satisfied with the Content quality of the app or not	Yes	1
			No	0
16.	Reliability	If the app completes the Stress test or not	Success	1
			Fail	0
17.	Security	Does the app provide a shield against probable harm to personal data or any malicious action?	Yes	1
			No	0
18.	Design Quality	Whether the user is satisfied with the design quality of the app or not	Satisfied	1
			Not Satisfied	0
19.	Usefulness	Professed usefulness, functionality, and services	Yes	1
			No	0
20.	Performance	The performance of an app depends on the RAM and CPU utilization of the App	0-20 Mb Ram & < 20 % CPU	1
			0-20 Mb Ram & 20%-50% CPU	2
			0-20 Mb Ram & > 50% CPU	3
			>20 Mb Ram & < 20 % CPU	4
			>20 Mb Ram & 20 % - 50% CPU	5
			>20 Mb Ram & > 50 % CPU	6

(Table 2 Contd ....)

(.... Contd Table 2)

21.	Social Media Integration	The app has options with Facebook, Instagram, or another social network	Yes	1
			No	0
22.	Regularly Updated	Whether the app is regularly updated or not	Yes	1
			No	0

The average rating column is considered as targets/labels for classifier Models. As App success is based on the average rating, there is a need to categorize the target as follows

- The Avg rating below 2.0 is considered a failed application under category (0).
- The Avg rating between 2.0 and 3.0 is considered a limited success application under category (1).
- The Avg rating above 4.0 is considered a successful application under category (2).

There were 22 features in the dataset. Only 18 were selected after understanding the meaning and suitability for statistical analysis and modeling. The final selected features are LOC, APK Size, Avg Rating, Installs, Version, Free/ Paid, Subjective Norms, Perceived compatibility, Perceived Playfulness, Satisfaction, Perceived Usefulness, Perceived ease of use, Content Quality, Reliability, Security, Design Quality, Usefulness, Performance, Social Media Integration, Regularly Updated.

4. Machine Learning Models

Five Machine Learning models were selected as our problem is a classification problem (success or failure). The selected ones are as follows:

1. **Logistic Regression Classifier** [37], LRC is used for binary classification where the sigmoid function is used, which takes input as independent variables and produces a probability value between 0 and 1. Logistic regression is a technique that is limited to classification issues. Because it uses the logistic function (Sigmoid) as the activation function to separate the data into distinct classes, it can only be taken into consideration for classification problems, although it shares characteristics with linear regression. It is a popular technique in research on classification [38], [39].
2. **Naive Bayes Classifier** [40], NBC is based on Bayes' Theorem, which describes the probability of a certain event, based on prior knowledge of conditions that might be related to this event. Using Bayes' Theorem to classify data according to the probability of various classes given the data's attributes is the fundamental concept of the Naive Bayes classifier [41]. The majority of its applications are in high-dimensional text classification. Naive Bayes classifiers use the Bayes theorem to categorize events into classes. They belong to the category of extremely effective classification algorithms due to their accuracy and simplicity. Naive Bayes classifiers classify unknown events by calculating the likelihood of each class occurring and then choosing the class with the highest probability. They are regarded as very efficient supervised classifiers because of their minimal calculation time and high degree of accuracy[42].
3. **Decision Tree classifier** [43], DTC's purpose is to generate a model that predicts a target based on input features using Tree models. In these models, leaves represent class labels, and feature conjunctions that lead to those class labels are represented by branches. Data instances and attributes are represented hierarchically in a Decision Tree (DT). Regression and classification tasks are both handled by decision trees (DTs). Decisions are made in decision nodes, and a tree shape is constructed with a root node as the starting node. A DTC's primary benefit is the minimal amount of computing time needed after it is created. However, the primary disadvantage of the DTC is the determination of the sequences of these nodes, which can be changed to create multiple DTCs by altering the root or decision nodes [44], [45] .
4. **Support Vector Machine classifier**[37], SVM is considered a robust classifier that aims to find an optimal hyperplane that divides feature space by finding how far the margin is from the hyperplane, and the traits that are closest across all classes. Following the classification of the data and the mapping of the data into hyperspace using a kernel function, support vectors—the data points of each class that are nearest to one another—are assigned in SVM. Consequently, the classification uses a subset produced by the input data's support vectors to reduce the separation between the input data points and the hyperplane [46].
5. **Gradient Boosting Classifier** [47], Another type of tree-based ensemble machine learning algorithm after

the Decision Tree classifier is gradient boosting. GBC is a powerful boosting algorithm that combines several weak learners into strong learners, in which each new model is trained to minimize the loss function. By taking into account the loss experienced by the weak learners, who are also Decision Trees, it maximizes the outputs. A freshly built or altered Decision Tree is added to use a gradient descent approach to minimize the overall loss. The gradient boosting approach works well for tasks involving classification and regression [48], [49].

5. **Prediction:** The ML models are used to fit the model and predict the values after splitting the dataset into training (75%) and testing (25%). The time (in seconds) is also recorded for each classifier to compare the performance metric.

6. **Performance Evaluation:** For performance evaluation, the F1-score accuracy data instances and attributes are represented hierarchically in a DT. Regression and classification tasks are both handled by decision trees (DTs). Decisions are made in decision nodes, and a tree shape is constructed with a root node as the starting node. A DT's primary benefit is the minimal amount of computing time needed after it is created. However, the primary disadvantage of the DT is the determination of the sequences of these nodes, which can be changed to create multiple DTs by altering the root or decision nodes [30], [50], [51] measure is used, which ranges from 0.1 to 1.0. For the reliability of the models, K-fold cross-validation [50] is used.

The results in Table 3 for F1-scores show that the best prediction accuracy is for Logistic Regression, Gaussian Naïve Bayes, and the SVC ML classifier with 96% accuracy. Performance-wise wise Gradient Boosting succeeded with 0.0082 seconds, making it the fastest training algorithm among the other four algorithms.

Table 3: Accuracy Measure of the ML Classifiers using F1-Score

Machine Learning Classifiers	F1-Scores		Time Elapsed	
	Training	Testing	Training	Testing
Logistic Regression	0.9067	**0.9600**	0.0291	0.0122
Gaussian Naïve Bayes	0.9067	**0.9600**	0.0175	0.0130
Decision Tree	1.000	0.800	0.0172	0.0093
SVC	1.000	**0.9600**	1.0140	0.0224
Gradient Boosting	1.000	0.9200	0.2539	**0.0082**

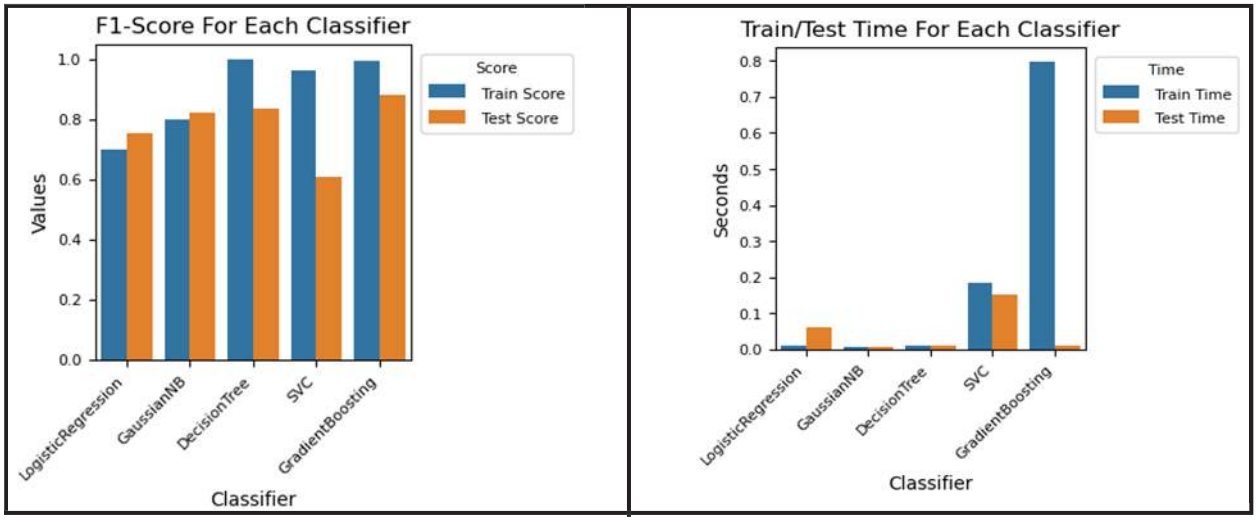

Fig. 2: Comparison of Machine Learning Classifiers

The cross-validation technique is used to test the classifier's reliability in this study. Cross-validation divides the training data into k parts (k=10 in this implementation), then uses 9 parts as a training dataset and tests with the remaining part (validation dataset). This operation is repeated 10 times, then the final result is the average score of 10 trials. The results of cross-validation are presented in Table 4. Logistic Regression and SVC, again, prove that they are the most reliable classifiers with mean scores of 0.91.

Table 4: ML Classifiers Reliability Measure using Cross-Validation

Machine Learning Classifiers	Training	Testing
Logistic Regression	0.910	**0.910**
Gaussian Naïve Bayes	0.880	0.90
Decision Tree	1.00	0.850
SVC	1.000	**0.910**
Gradient Boosting	1.000	0.90

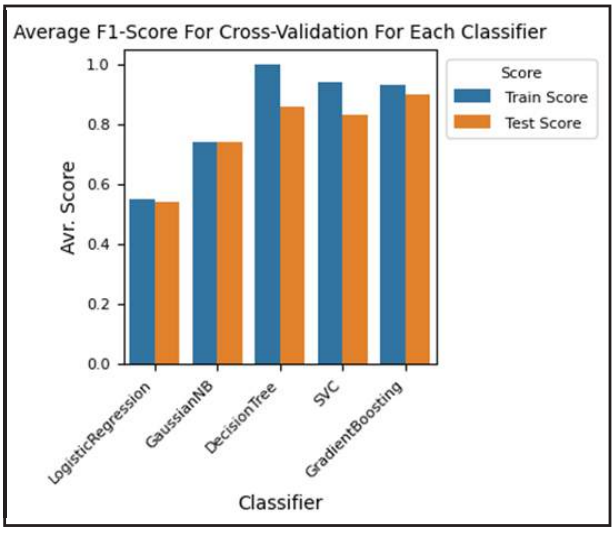

Fig. 3: Cross-Validation Score for ML Classifier

CONCLUSION AND FUTURE WORK

This study report presents the current state-of-the-art for success prediction of mobile app software before its launch on the Play Store. 14 critical success factors of mobile apps that play a very important role in their success on the Play Store are identified in the literature and are further investigated through an online survey of various mobile app users. The research gap indicates that critical success factors are currently not considered by existing approaches to predict success. There is no formal model that solely reflects these factors. This study successfully implemented machine learning models (using Python Jupyter Notebook 7.0.8) to predict the 'Average rating' of an app as a success predictor. A developer can now first predict whether an app will be successful, limited successful, or failed, with a given set of features, after being uploaded to the Google Play store. The accuracy of the final selected model is 96%, which is the highest accuracy among many existing models in the literature. In the future, to further enhance the model accuracy, one can try to tune classifier parameters instead of using default values or try a Neural Network for classification.

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DISCLOSURE OF INTERESTS

The author has no competing interests to declare that are relevant to the content of this article.

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Optic Nerve Head Info Injected K-Means Method for Segmentation of OD

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Abstract—Segmenting the Optic Disc (OD) is an important step in the automated detecting of certain serious ocular illnesses. An innovative strategy for segmenting the OD is critical since it faces challenges such as vascular obstruction, low contrast, and poor accuracy. This paper proposes a new method for OD segmentation, namely 'OD segmentation using Optic Nerve Head info injected K-Means method (ONHKM)'. By adding Optic Nerve Head (ONH) structural information through an iterative procedure, the proposed method improves upon the standard K-means segmentation algorithm. Through this integration, the membership matrix is updated gradually based on the ONH structure information that improves the segmentation and identification of the OD region. The contributions through the exclusive membership update and objective function update, make up the ONH structure-specific OD enhancement. The ONH structure-specific membership modification enhances the efficiency of OD segmentation, while the modified OD structure-specific objective function leverages the execution speed of the convergence process. The proposed ONHKM method exhibited an impressive average segmentation accuracy of 97.52% compared to existing methods. The efficacy of the method is shown by this major enhancement, which can be effortlessly incorporated into fundus scanners, offering a useful and dependable tool for medical use. According to the results, the ONHKM method improves automated OD segmentation, which will hopefully assist with ocular disease early diagnosis and treatment.

Keywords: Medical image processing, K-means, Fundus image, OD segmentation, Optic nerve head

INTRODUCTION

The ability to observe the world around us is made possible by the amazing human eye. Its intricate structure and functions enable the reception, transmission, and processing of visual information, that contributes to our perception and understanding of the environment. The inner lining of the eye, more precisely the portion of the eye that is visible via the ophthalmoscope at the back, is referred to as the 'fundus' [1] in medical terminology. It contains the OD, Blood Vessels (BV), retina, and other tissues that can be looked at during an eye exam. The OD [2], often referred to as the optic nerve head, is a crucial component located at the back of the eye where the optic nerve exits the eye and enters the brain. In the center of the retina, it appears as an oval or circular region. It is a crucial part of the fundus, which is the surface of the eye's interior seen through an ophthalmoscope [3]. Identifying the borders of the optic disc in retinal images is a technique known as OD segmentation [4], which can be done either automatically or manually. It is an important

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stage in the analysis of retinal images for the diagnosis and monitoring of different eye diseases and conditions. Accurate OD segmentation enables additional examination of the OD, including measurements of its shape, size, and other parameters. It helps in the detection and monitoring of retinal diseases such as glaucoma, Diabetic Retinopathy (DR), and disorders of the optic nerve because it allows the detection and tracking of changes over time.

A medical imaging technique called fundus photography [5] is used to capture complete images of the retina, OD, macula, and BV that make up the fundus, which is the inner surface of the eye. It is a useful tool for ophthalmologists to diagnose and monitor different eye diseases and disorders.

Ahmed *et al.* [6] discovered a method to identify the midpoint of the OD by using the mean intensity value of the retinal image. This method can be applied to improve the detection of retinal OD or to diagnose retinal disorders. An RGB fundus image's green channel is used to inform a candidate-based method that locates the OD center. This method's excessive computational cost makes it inappropriate. Carmona *et al.* [7] predicted a technique for simultaneously segmenting medical image anatomical characteristics. Similarly, this method is applied in a way that segments the fovea and OD of retinal images simultaneously. Identifying the OD and fovea as crucial anatomical structures is required for any image-based computer-aided diagnosis system designed to diagnose retinal diseases that cause vision loss. The simultaneous segmentation technique makes use of the evolutionary algorithm and the OD Fovea model. It only segmenting a smaller amount of anatomical structure is its inferiority.

Gonzalez *et al.* [8] created the retinal fundus image segmentation method using OD and BV. Herein, segmenting the OD can be done in two different ways namely, Markov Random Field (MRF) and Compensation Factor Method (CFM). It fails in the segmentation of retinal diseases. Miri *et al.* [9] evaluated a multimodal method to utilize the interrelated information from Spectral Domain Optical Coherence Tomography (SD-OCT) and fundus images. OD and OC segmentation is done automatically using this multimodal machine learning graph-based method. The unworthiness of this method is that the blood vessel removal is not included.

Zhang *et al.* [10] provided an OD detection method based on the directional and vessel distribution properties. Herein, three-vessel distribution properties local vessel density, compactness, and uniformity are combined into one feature design to identify an accurate horizontal coordinate of OD. The vertical coordinate of OD is calculated using a General Hough Transformation (GHT). Due to the processing of small-sized images, the range of accuracy in the OD border is quite low. Wu *et al.* [11] offered a method based on directional models for automatically localizing ODs in retinal fundus images. The method uses three different directional models: the hybrid directional model, the local Directional Model (DDM), and the global directional model (R-BPDM). The disfavor of this work is that the performance side is low.

Roychowdhury *et al.* [12] devised a classification method that identifies both the Vessel Origin (VO) pixel and the OD boundary using an OD segmentation method. The bright regions are divided into bright probable OD regions and non-OD regions using six region-based features and a Gaussian Mixture Model (GMM) classifier. It fails to identify the disease severity, which is the fault of this method. Zahoor *et al.* [13] illustrated an image processing pipeline for automatically detecting glaucoma in retinal images. The Region Of Interest (ROI) used for OC segmentation is the segmented OD. Multi-layer perceptrons (MLP) are utilized for the supervised categorization of OC pixels. A decision tree-based ensemble classifier is used to categorize the glaucomatous images. The mistake of this paper is that it marks the OD region using a standard elliptic model.

Khalil *et al.* [14] portrayed a method to increase the accuracy of the extraction of the Inner Limiting Membrane (ILM) layer. It utilized a method to enhance the shape of the ILM layer. The method applied Bezier curve fitting and interpolation in terms of surface refinement and outlier removal. The downside of this method is that the degeneration of ganglion cells has not been examined while retinal layers are taken into consideration.

Huazhu Fu *et al.* [15] suggested a deep learning method to test for glaucoma directly from the fundus image and obtain extra image-relevant information. The Disc-aware Ensemble Network (DENet) method is used for glaucoma screening. There are four deep streams with different levels and modules: local disc area stream, disc polar transformation stream, segmentation-guided network, and global image stream. The time consumption is high, which is the failure of this method. Huazhu Fu *et al.* [16] depicted M-Net, a deep learning architecture that integrates OD and OC segmentation in a one-stage multi-label system. The major components of M-Net are the multi-label loss function, side-output layer, U-shaped convolutional network, and multi-scale input layer. The failure of this work is that the time consumption is high.

Lei *et al.* [17] revealed an unsupervised domain adaption-based image synthesis and feature matching for OD and OC segmentation. Using boundary data from the OD and OC, the GAN-based Image Synthesis (IS) method is used. Here, the methods of Output-Level Feature Alignment (OLFA) and Content and Style Feature Alignment (CSFA) are applied. The insignificance of this method is the high time and computational complexity of the training network. Veena *et al.* [25] established the segmentation of OD and OC for the automated identification of glaucoma. Accurate segmentation is achieved by the deep learning architecture method using an enhanced version of each of the two CNN models for OD and OC separately. The imperfection is quite time-consuming.

Chen *et al.* [27] presented a Reconstruction-driven Dynamic Refinement Network (RDR-Net), a unique Unsupervised Domain Adaptation (UDA) technique, in which it developed three modules namely, the Reconstruction Alignment (RA) module, Low-level Feature Refinement (LFR) module, and Prediction-Map Alignment (PMA) module to reduce the domain gap and use a due-path segmentation backbone for simultaneous edge detection and region prediction. The flaw of this method is poor region prediction. Meng *et al.* [28] exposed OD and OC segmentation from retinal fundus images. It exhibits a weakly and semi-supervised graph-based network that explores three features of geometric relationships and domain knowledge between segmentation Probability Maps (PM), modified Signed Distance Function representations (mSDF), and Boundary Region Of Interest characteristics (B-ROI). The imperfection of this work is that its algorithm performance is low.

Liu *et al.* [29] devised an adversarial network-based combined segmentation method for the OD and OC, which includes additional monitoring features to direct the network optimization process. This framework was evaluated with two publicly available performance datasets of retinal fundus images. The inadequacy of this work is that the image quality is low. Virbukaite *et al.* [30] portrayed a Convolutional Neural Networks (CNNs) based ensemble for joint optic disc and optic cup segmentation. It used a modified Attention U-Net architecture with pre-trained ResNet34, ResNet50, MobileNet, Inceptionv3, and DenseNet121 as backbones. The minus of this work is that it provided less accuracy.

Multiple methods of OD segmentation have been published in the literature, but they have a few difficulties, like high time consumption, suffering from less accuracy, and OD regions having various appearances due to size, shape, color, and texture across different retinal images. The boundary of the OD is often indistinct because of the blend with the surrounding retina, blood vessels, and other structures, which makes it difficult to precisely determine the disc's boundary. This paper concentrates on the development of an OD segmentation method using fundus images. As a result, this study proposed a segmentation technique called the 'Optic nerve head info injected k-mean method'. The main contributions of the proposed method for OD segmentation using the Optic Nerve Head info injected K-Means method (ONHKM) are as follows:

The proposed ONHKM method's main contribution is the ONH structure-specific membership computation that is injected K-means clustering method.

The membership function of the K-mean algorithm is framed as an upgraded version of membership calculation through the ONH structure-specific modification.

The intermediate segmented result of the OD region is further enhanced by the horizontal directional filling, which is also considered an innovative approach.

A new objective function for K-mean clustering is designed by concentrating the successive modifications in the structure of the OD region to achieve faster convergence.

This paper presents a novel method that uses Optic Nerve Head (ONH) data to calibrate the K-means segmentation algorithm. The membership matrix can be updated gradually through this iterative method, improving the accuracy of OD segmentation. A two-part ONH structure-specific enhancement is integrated into the study. This consists of an exclusive membership update and an OD enhancement phase, both of which greatly increase the segmentation accuracy. The proposed ONHKM method outperforms previous techniques and demonstrates the method's effectiveness with an astounding average segmentation accuracy of 97.52%. Combining these efforts, a method to OD segmentation becomes more precise and dependable by addressing issues like low contrast and vascular blockage.

The proposed ONHKM method for OD segmentation is explained in Section 2 along with its working process. An explanation of the proposed ONHKM method based on standard measures, the analytical results, and discussions are covered in Section 3. The efficiency of the proposed method in comparison to existing methods is concluded in Section 4.

PROPOSED METHOD

The OD area is segmented from the input fundus image by the proposed ONHKM method. Figure 1 depicts the process of this method's workflow. There are three color channels Red, Green, and Blue in the input color fundus image. Among these three channels, the Red channel points out the OD region much clearer than the other two; hence, the proposed method uses the Red channel as the source for the improved K-means algorithm that is supported by the ONH structure of the fundus image. Figure 1, shows the block diagram of the proposed ONHKM method for OD.

In Figure 1, the process begins with the input of a fundus image, which is a retinal image captured using a fundus camera. The red channel from these images is extracted, which is often used because it provides better contrast for retinal features. The red channel data undergoes an improved K-means initialization process. This is likely used to initialize cluster centroids more effectively, leading to better segmentation results. As part of the K-means algorithm, the central head (centroid) of clusters is computed. The distance between data points and cluster centroids is calculated to assign each point to the nearest cluster. Based on the distance, the membership of each data point to a particular cluster is determined. After several iterations, three clusters are formed, which likely correspond to different regions or structures within the retina. The process further refines the clusters based on specific characteristics of the optic nerve head (ONH). Enhancing the OD to ensure it is correctly identified and segmented. Herein, it updates the cluster memberships to improve the accuracy of segmentation. An objective function is used to optimize the segmentation process, ensuring that the biggest object detected within the image corresponds to the OD region. The segmented regions are analyzed to identify the largest object, which is assumed to be the OD. Finally, the segmented OD region is identified and extracted as the final output. The process aims to accurately segment the OD from retinal images using a combination of image processing techniques and clustering algorithms

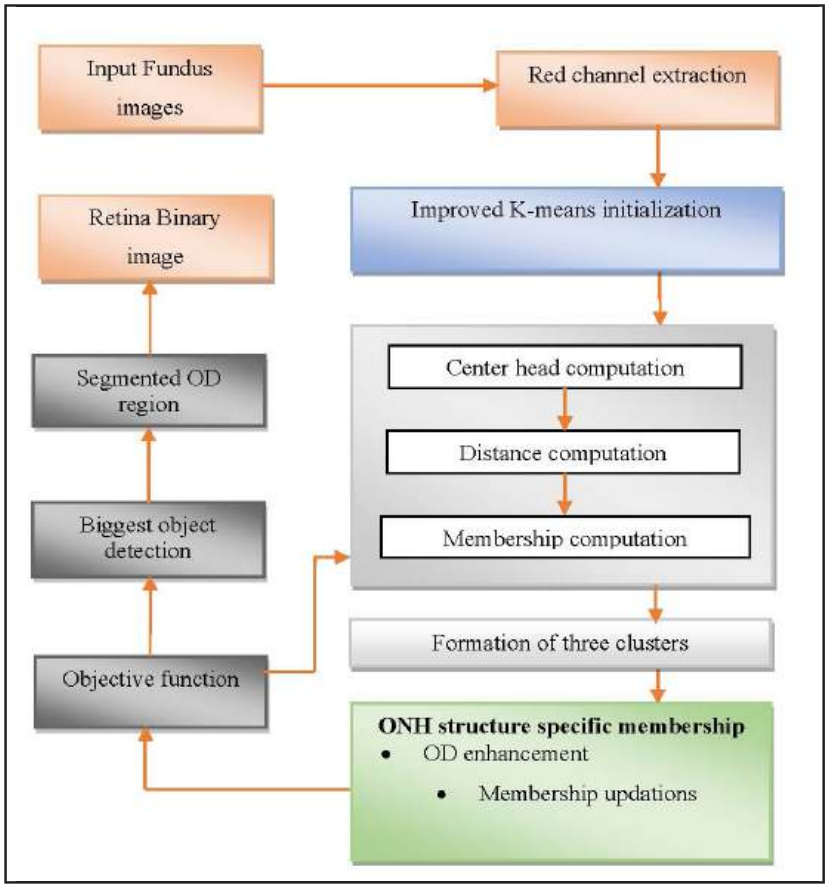

Fig.1: Block Diagram of the Proposed ONHKM Method for OD

The K-means [18] algorithm is used to cluster the meaningful region of an image. It is a famous and effective image segmentation method worldwide. It segments the image into K segments; hence, that name is given to this algorithm. The selection of the K-Means method for OD segmentation in this study is based on several key factors, including computational efficiency, interpretability, and adaptability to fundus imaging constraints. While deep learning-based approaches and adaptive clustering methods have demonstrated high accuracy in medical image segmentation, they often come with significant drawbacks, such as:

- Computational Complexity & Hardware Dependence
- Data Dependency & Generalization Issues:
- Interpretability & Clinical Acceptance
- Performance vs. Complexity Trade-off

Thus, while deep learning and adaptive clustering methods are powerful, the ONHKM method balances accuracy, efficiency, and practicality, making it an optimal choice for real-time and resource-constrained medical applications.

The input fundus image's Red channel is fed as input to the K-means algorithm. The image containing the height '*h*' and width '*w*' is linearly converted into vector form and named '*x*'. It can be expanded as $x = \{x_0, x_1, x_2, \ldots\ldots\ldots, x_{m\times n}\}$. The total element's length is noted as $L = m \times m$. The total cluster P is fixed as 3. The reason for the three clusters is the availability of data such as background, OD region, and another retina region. A membership matrix M, which contains zeros and 1, is constructed in the random format. The dimension of the membership matrix is set to $L \times P$, which obeys Eq. (1).

$$\sum_{j=0}^{p-1} M_{i,j} = 1 \tag{1}$$

There must be only one 1 in any of the three clusters of data of i_{th} element, and other positions should be zeros. The exponent value q is set to 2. The maximum iteration *mitt* is fixed as 50. The cluster head information is noted as $C_j$where, $j \in [0, p-1]$ and it is computed using Eq. (2).

$$cj = \frac{\sum_{i=0}^{L-1} (M_{i,j})^q \times x_i}{\sum_{i=1}^{n-1} M_{i,j}^q} \tag{2}$$

$$j \in [0. p-1]$$

The distance between each pixel and cluster head C_j is computed using Eq. (3).

$$d_{i,j} = ||x_i - c_j|| \tag{3}$$

According to Eq. (3), the minimum distance value providing cluster index is the much more closed cluster index related to the x_i data. This association of a specific cluster is stored in the membership matrix M by specifying 1, and for other locations, it is 0. It can be spelled Eq. (4), Eq. (5) and Eq. (6).

$$M_{i,j} \in [0, p-1] = 0 \tag{4}$$

$$I = Func_Min_Index\ (d_{i,0,}\ d,\ d_{i,2}) \tag{5}$$

$$M_{i,j} = 1 \tag{6}$$

where

I - Index of minimum value

In Eq. (4), the entire clusters of i^{th} elements are set to zero. Afterward, the minimum value providing an index of the three clusters is found using Eq. (5). Herein, *Func_Min_Index* refers to the function to compute the minimum index value.

The ONH structure-specific modification is set into the membership matrix through some processes. First, the membership matrix is utilized to get the partially segmented image, which contains the three labels such as 0, 1, and 2. This intermediate process is performed at 20th iterations to confirm the formation of the three clusters. The partially segmented image is converted into three binary images, and the mean of their foreground data is computed. The mean values of the three clusters are noted as μ_o, μ_1, and μ_2. Generally, the OD region is formed with high-intensity data; hence, the cluster info related to high intensity is fixed as the mean intensity of the OD region. This process is given in Eq. (7).

$$\mu = Func_Max\ (\mu_0, \mu_1, \mu_2) \tag{7}$$

where

μ – Mean of OD area

The minimum providing clusters index value is noted as OD_{IND}, and it can be expressed using Eq. (8).

$$OD_{IND} = Func_Max_Index\ (\mu_0, \mu_1, \mu_2) \tag{8}$$

The OD region-oriented binary image is enhanced by filling the gaps in between the OD surface in the horizontal direction. Herein, the OD region is sliced row by row and the gaps are filled by 1s, hence the structure of the OD region is enhanced. The binary segmentation contains multiple bounded regions, and they can be eliminated to get the OD region only by using the biggest object detection method.

The OD region-specific pixels updated their membership matrix info by setting 1 for their O_{DIND} cluster index, and 0 for other cluster indexes. The linear vector x is altered by the OD mean intensity value. This phenomenon is shown in Eq. (9), Eq. (10), Eq. (11) and Eq. (12).

$$\alpha = OD_{IND} \tag{9}$$

$$M_{r*w+c,} j \in [0, p-1] = 0 \tag{10}$$

$$M_{r*w+c}, \alpha = 1 \quad (11)$$

$$x_{r*w+c} = \mu \quad (12)$$

where

γ – Current pixels row

C – Current pixels column

Now, the membership matrix M and the linear vector x are altered based on the ONH structure. This process enhances the OD region through the iterations of K-means segmentation that perform in a specific interval of 4.

After the formation of three clusters, the objective function is implemented using Eq. (13).

$$k = \mathrm{OD}_{\mathrm{IND}}$$

$$fn_obj\ (itt) = \sum_{i=0}^{n-1} D_{i,k}^2 \times MM_{i,k} \quad (13)$$

In Eq. (13), the convergence property computation is performed only for the OD-oriented cluster index, which is OD_{IND}. In other words, the $\mathrm{OD}_{\mathrm{IND}}$ based modification quantity calculation is progressed instead of the entire cluster, which is much enough for an intelligent convergence determination system because in this work the target is only the OD region. The term *itt* refers to the current iteration progressed in the K-means clustering process. If the difference between the continuous values of the objective function is very small, then the iterative process is terminated; otherwise, it loops up to the maximum iteration *mitt*. The segmented image is drawn out using the membership matrix. The OD_{IND} index-oriented binary image is extracted, and the biggest object is found to extract the OD region. The real intensity information from the input image is projected in the OD region to show the segmented output. In this way, the proposed ONHKM method effectively segments the OD region from the fundus image.

Algorithm for Optic Nerve Head Info Injected K-Means (ONHKM)

Input:

- Dataset X with n data points (image pixels/features)
- Number of clusters K
- Optic Nerve Head (ONH) information (e.g., region mask, center coordinates)
- Maximum iterations (optional)

Output:

- K cluster centroids
- Cluster assignments for each data point

Step 1: Initialize

1. Extract ONH-related information from the image
2. Assign higher weight or priority to data points near the ONH region
3. Select K initial centroids, ensuring at least one centroid is near the ONH region

Step 2: Iterate until convergence or max iterations

4. Assign each data point to the nearest centroid
   - For each data point xi in X:
   - Compute weighted distance based on ONH influence
   - Assign xi to the cluster with the closest centroid
5. Update cluster centroids
   - For each cluster j (1 to K):
   - Compute the weighted mean of all points assigned to cluster j
   - Update the centroid accordingly
6. Check for convergence
   - If centroids do not change significantly, stop iteration

Step 3: Return final cluster centroids and data assignments

DISCUSSION AND ANALYSIS

The effectiveness of the novel method is illustrated in this section by evalu[a]ting the proposed ONHKM method with alternative methods for segmentation. This analysis contains three existing methods to aid in the evaluation of the proposed method. Those three existing segmentation techniques are known as:

- OD Segmentation using Morphological Adaptive Fuzzy Thresholding based OD segmentation (ODSMAFT) [19]
- OD Segmentation using Region-based Convolutional Neural network-oriented OD segmentation (ODSRCNN) [20]
- OD Segmentation using Fuzzy Broad Learning System based OD segmentation (ODSFBLS) [21].

Different benchmark datasets are used to analyze the proposed OD segmentation method ONHKM. These four fundus image datasets are used for this analytic component. They are:

- Kaggle Fundus Image DataSet (KFI) [22]

- Retinal Fundus Multi-disease Image Dataset (RFMI) [23]
- ChaseDB1 database (CHASEDB1) [24]
- STructured Analysis of the REtina DataSet (STARE-DS) [31].

The ability of an algorithm to identify and respond to the changes in the input image is referred to as 'Average Sensitivity' (AS), which measures the percentage of actual positive values that are correctly identified in OD segmentation fundus images. Using Eq. (14), the average sensitivity measurement is calculated.

$$AS_{OD} = \frac{TP}{TP + FP} \tag{14}$$

AS_{OD} – Average Sensitivity for OD Segmentation

TN – Pixels count of True Positive for background

FN – Pixels count of False Positive for background

Table 1: AS Analysis for OD Segmentation

Dataset	Average Sensitivity			
	ODSMAFT	ODSRCNN	ODSFBLS	Proposed ONHKM
KFI	0.925	0.932	0.941	**0.946**
RFMI	0.932	0.937	0.944	**0.950**
CHASEDB1	0.928	0.934	0.942	**0.947**
STARE	0.926	0.933	0.942	**0.947**

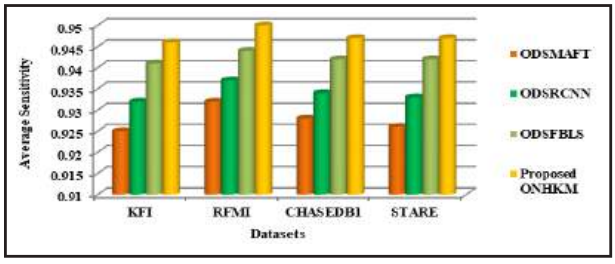

Fig. 2: Chart for Average Sensitivity

Table 1 and Figure 2 expose the average sensitivity [8] on OD segmentation in four databases such as KFI, RFMI, CHASEDB1, and STARE. The proposed ONHKM method achieves the highest average sensitivity value of 0.950 in the RFMI dataset. The ODSMAFT method exposes the least performance in this analysis.

Segmentation Accuracy (SA) measures the quality of segmentation of objects of interest from images, which is a crucial factor in determining their performance. In this work, segmentation accuracy is measured to compare the performance level of the proposed and existing methods in OD segmentation. The Segmentation accuracy is computed using Eq. (15).

$$AS_{OD} = \frac{TP + TN}{TP + FP + TN + FN} \tag{15}$$

where

SA_{OD} – Segmentation Accuracy for OD Segmentation

TN – Pixels count of True Negative for background

FN – Pixels count of False Negative for background

Table 2: Segmentation Accuracy for OD Segmentation

Dataset	Images	Segmentation Accuracy			
		ODSMAFT	ODSRCNN	ODSFBLS	Proposed ONHKM
KFI	KFI-0	95.11	96.06	96.39	**96.77**
	KFI-1	95.32	96.2	96.56	**96.96**
	KFI-2	95.24	96.13	96.49	**96.85**
RFMI	RFMI-0	95.85	96.65	96.92	**97.38**
	RFMI-1	95.7	96.54	96.79	**97.25**
	RFMI-2	95.53	96.42	96.68	**97.15**
CHASEDB1	CHASEDB1-0	95.39	96.33	96.71	**97.16**
	CHASEDB1-1	95.55	96.41	96.84	**97.25**
	CHASEDB1-2	95.26	96.23	96.6	**97.04**
STARE	STARE-0	95.12	96.07	96.40	**96.78**
	STARE-1	95.33	96.03	96.57	**96.97**
	STARE-2	95.25	96.14	96.50	**96.86**

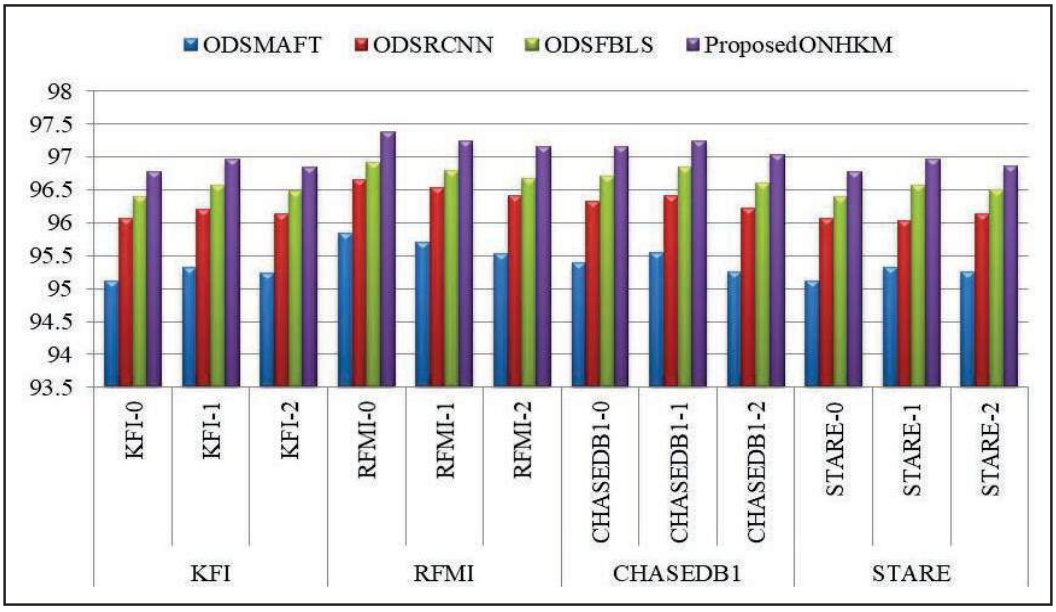

Fig. 3: Chart for Segmentation Accuracy

Table 3: Time-taken Analysis for OD Segmentation

Database	Time Taken (in sec)			
	ODSMAFT	ODSRCNN	ODSFBLS	Proposed ONHKM
KFI	5.52	6.05	6.42	**5.89**
RFMI	5.43	5.83	6.21	**5.71**
CHASEDB1	5.51	6.01	6.34	**5.80**
STARE	5.53	6.06	6.43	**5.90**

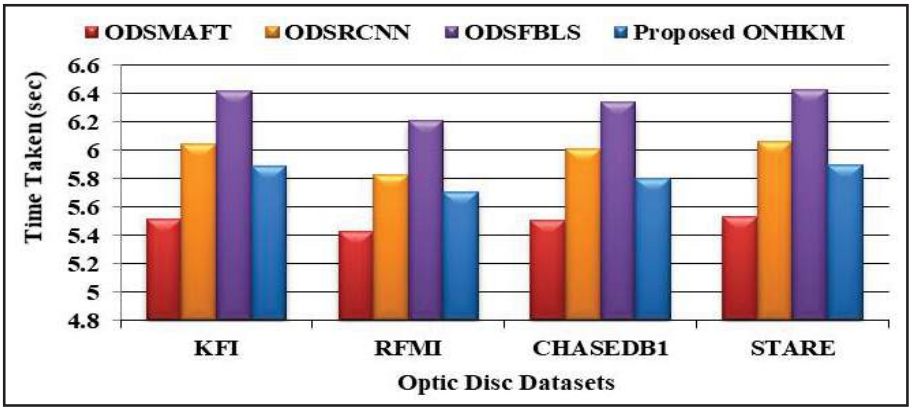

Fig. 4: Average Time taken Analysis for OD Segmentation

The segmentation Accuracy on OD segmentation is revealed in Table 2 and Figure 3. Herein, the three different images of four different databases, i.e., KFI, RFMI, CHASEDB1, and STARE are chosen for this analysis. The proposed ONHKM method provides a high accuracy value of 97.39. The second-best accuracy value is 97.25. The lowest performance accuracy value is 96.77.

The time taken for optic disc segmentation is an important metric of the segmentation algorithm's efficiency and scalability in real-world scenarios. In Figure 4, a chart represents the time occupied in seconds between the 'beginning' and 'end' of the optic disc segmentation process. The resulting values are listed in Table 3.

The time taken for OD segmentation analysis for the four datasets, including KFI, RFMI, CHASEDB1 and STARE, is shown in Table 3 and Figure 4. In this time-taken analysis, the execution time is calculated using 100 photos from each dataset. Comparing the proposed ONHKM method to the other three existing methods, it evaluates all three datasets in a significantly shorter amount of time. The RFMI dataset shows an outstanding average of 5.71 seconds according to the proposed method. The performance of the KFI dataset in the overall technique comparison is awful in the time taken analysis.

A Ranking Index Metric (RIM) could refer to a particular score or measurement that is used to evaluate and contrast ranks. In actual use, it might stand for the effectiveness of various algorithms, the usefulness of search results, or the effectiveness of a recommendation system.

Table 4: Ranking Index Metric Analysis

METHOD	KFI	RFMI	CHASEDB1	STARE
ODSMAFT	1	1	1	1
ODSRCNN	2	2	2	2
ODSFBLS	3	3	3	3
Proposed ONHKM	**4**	**4**	**4**	**4**

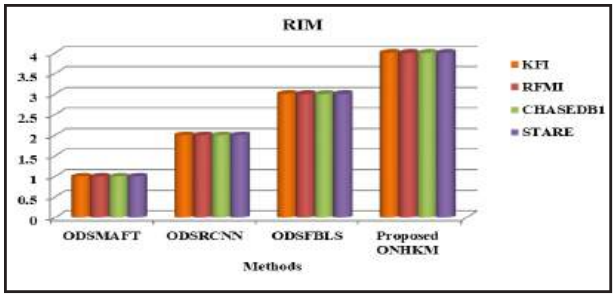

Fig. 5: Chart for Ranking Index Metric

Here, Table 4 and Figure 5 reveal the analysis result using Ranking Index Metric (RIM) in OD segmentation. According to SA, Sensitivity, the proposed ONHKM method gets a high rank of 4. The ODSFBLS method gets the rank of 3. The ODSRCNN method gets a rank value of 2. The ODSMAFT method gets the worst rank value of 1.

Table 5: Statistical Validation Result

Method	Statistical Validation
ODSMAFT	95.28
ODSRCNN	95.69
ODSFBLS	95.12
Proposed ONHKM	94.58

Table 5 portrays the statistical validation analysis result of the proposed ONHKM and chosen existing methods to ensure the reliability of the proposed method.

This research segments the OD region from the fundus image, and it is validated using soft and hard models. This study validates the effectiveness of the proposed OD segmentation method using four comprehensive datasets. This process involves comparing the segmentation results against ground-truth annotations provided by expert radiologists. This research uses the datasets comparing 200 images with varying OD sizes and locations to ensure a thorough evaluation. The performance of the segmentation method is evaluated using standard metrics, including sensitivity, segmentation accuracy, time taken, RIM, and statistical validation analysis result. Comparative analysis is done using benchmarked existing methods such as ODSMAFT, ODSRCNN, and ODSFBLS. The proposed ONHKM method outperformed traditional methods by achieving better sensitivity, segmentation accuracy, time taken, RIM, and statistical validation analysis result across different cases. Visual inspection of the segmentation results confirmed that our method effectively delineates OD boundaries even in cases with complex OD shapes and heterogeneous tissue structure. The validation results indicate that the proposed OD segmentation method is both accurate and reliable, making it a tool for clinical applications such as,

- **Early Disease Detection:** OD segmentation plays a critical role in the early detection of glaucoma, diabetic retinopathy, and other optic neuropathies. By improving segmentation accuracy, ONHKM can enhance the reliability of automated screening systems, aiding ophthalmologists in early diagnosis.
- **Integration with Fundus Imaging Systems:** The method is computationally efficient and can be seamlessly integrated into existing fundus cameras and diagnostic tools, providing real-time assistance without requiring complex deep learning models or extensive datasets.

- **Enhanced Decision Support for Clinicians:** The interpretability of ONHKM makes it clinically practical, allowing doctors to visually verify the segmentation results and make informed decisions. Unlike deep learning methods, which often function as "black-box" models, our approach provides transparent and explainable segmentation results.
- **Potential Limitations & Future Directions:** Handling of Pathological Variations: While ONHKM achieves high accuracy (97.52%), extreme pathological variations (*e.g.*, severe optic disc cupping in glaucoma) might still pose segmentation challenges. Future work will involve fine-tuning ONHKM for pathological cases.
- **Cross-Dataset Generalization:** Clinical fundus images vary significantly in quality, resolution, and illumination. We plan to validate ONHKM on larger, multi-source datasets to ensure generalizability across different clinical environments.

By addressing these aspects, we aim to bridge the gap between research and clinical practice, making ONHKM a practical, efficient, and reliable tool for ophthalmic diagnostics. We appreciate this valuable suggestion and will incorporate a detailed clinical discussion in our revised manuscript.

CONCLUSION

The OD region is segmented from the fundus images by the proposed ONHKM method. The K-mean algorithm is the base of its functioning. The OD region is successfully segmented from the fundus image using the proposed ONHKM method. The KFI, RFMI, CHASEDB1, and STARE. databases are used to demonstrate the strength of OD segmentation of the proposed ONHKM method. This paper offers an analysis of the performance of the proposed ONHKM segmentation method in comparison with the state-of-the-art segmentation methods, including ODSMAFT, ODSRCNN, and ODSFBLS. The average SA values for the KFI, RFMI, CHASEDB1, and STARE databases are 96.96, 97.38, 97.25, and 96.16 respectively, according to the proposed ONHKM method. The ODSFBLS approach achieves the second-best average sensitivity of 0.944, while the proposed ONHKM method reaches a high average sensitivity value of 0.950. The ODSMAFT approach yields the lowest average sensitivity value of 0.932. This paper's future work will be focused on creating a novel OD segmentation method using convolutional neural networks.

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Enhancing CNC Machining Precision Using AI-Based Process Monitoring and Control

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Abstract—This study investigates the impact of AI-based process monitoring and control on CNC milling optimization. AI integration led to a 50% increase in material removal rate (MRR), a 14.3% improvement in tool life, a 20% reduction in machining time, and a 20% decrease in energy consumption. By leveraging machine learning algorithms, real-time sensor feedback, and predictive analytics, AI dynamically adjusted spindle speed, feed rate, and cutting parameters to enhance machining efficiency. Digital twin simulations further optimized tool paths, reducing tool wear and improving precision. The results highlight that AI-driven CNC milling enhances productivity, reduces operational costs, and ensures sustainable manufacturing practices.

Keyword—AI in CNC milling, process optimization, predictive maintenance, digital twin, machining efficiency, smart manufacturing, tool wear reduction, sustainable machining.

INTRODUCTION

Computer Numerical Control (CNC) machining plays a critical role in modern manufacturing, offering high precision and repeatability. However, achieving optimal accuracy remains a challenge due to variations in tool wear, machine dynamics, and environmental conditions. Recent advancements in artificial intelligence (AI) have introduced intelligent monitoring and control mechanisms to enhance machining precision. AI-based process monitoring utilizes real-time data analysis, predictive modeling, and adaptive control to optimize machining parameters and minimize errors (Zhang *et al.,* 2023). Machine learning algorithms, coupled with sensor integration, enable predictive maintenance, anomaly detection, and automated adjustments, leading to improved product quality and reduced downtime (Li, Wang, & Chen, 2022). By leveraging AI-driven strategies, CNC machining can achieve superior efficiency, accuracy, and reliability, making it a transformative approach for the future of precision manufacturing.

LITERATURE REVIEW

AI-Based Process Monitoring in CNC Machining

Artificial intelligence (AI) has emerged as a transformative tool for improving CNC machining precision through advanced process monitoring. Several studies have demonstrated the effectiveness of AI in real-time data acquisition, anomaly detection, and predictive maintenance. For instance, Zhang *et al.* (2023) explored the role of machine learning algorithms in optimizing CNC machining by analyzing sensor data to detect tool wear and machine vibrations. Their study found that AI-based models significantly reduced machining errors and improved surface finish quality. Similarly, Li, Wang, and Chen (2022) highlighted the application of deep learning techniques in monitoring cutting forces and spindle speeds, enabling adaptive control mechanisms to maintain precision.

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AI-Driven Predictive Maintenance and Tool Wear Prediction

Predictive maintenance has become an essential application of AI in CNC machining. Traditional maintenance strategies rely on scheduled inspections, which can lead to unexpected breakdowns or unnecessary downtime. Recent studies suggest that AI-based predictive maintenance can optimize tool usage and extend equipment lifespan. Patel and Kumar (2021) demonstrated that convolutional neural networks (CNNs) could predict tool wear with over 90% accuracy, allowing for timely tool replacements and minimizing defects. Moreover, Singh *et al.* (2023) examined AI-integrated Internet of Things (IoT) solutions for predictive maintenance, emphasizing their ability to reduce maintenance costs and improve machine availability.

Adaptive Control and Autonomous Optimization

Adaptive control systems, driven by AI, have revolutionized CNC machining by enabling real-time parameter adjustments. Chen *et al.* (2023) reviewed various AI-based optimization techniques, including reinforcement learning and genetic algorithms, for dynamically adjusting feed rates and spindle speeds based on machining conditions. Their findings suggest that AI-enabled adaptive control reduces machining cycle time while maintaining tight tolerances. Furthermore, recent developments in digital twins have enhanced real-time process simulations, allowing manufacturers to preemptively correct deviations and optimize machining conditions (Zhao *et al.*, 2022).

Challenges and Future Prospects

Despite its advantages, AI-based CNC machining faces challenges such as data integration, computational complexity, and the need for skilled operators. Existing studies indicate that data-driven models require extensive training and high-quality datasets to ensure reliability (Gupta & Sharma, 2023). Additionally, cybersecurity concerns arise with the increasing adoption of IoT-enabled AI systems. Future research should focus on developing robust AI frameworks that can handle real-time uncertainties and integrate seamlessly with existing CNC infrastructure.

DIFFERENT OPERATION IN CNC MACHINING

CNC Milling

CNC milling uses rotary cutting tools to remove material from a workpiece. Common milling operations include:

i. **Face Milling**: Cutting a flat surface perpendicular to the spindle.

ii. **End Milling**: Cutting edges, pockets, and complex profiles.

iii. **Slot Milling**: Creating slots or grooves in a workpiece.

iv. **Contour Milling**: Following a curved or irregular path for complex shapes.

v. **Thread Milling**: Cutting screw threads using a rotating cutter.

CNC Turning (Lathe Operations)

CNC turning is used for cylindrical workpieces and involves rotating the material while a stationary cutting tool shapes it. Common operations include:

i. **Facing**: Creating a flat surface at the end of the workpiece.

ii. **Turning**: Removing material along the workpiece's length to achieve a desired diameter.

iii. **Boring**: Enlarging an existing hole to precise dimensions.

iv. **Grooving**: Creating narrow cuts or recesses in a workpiece.

v. **Thread Cutting**: Forming screw threads on cylindrical parts.

CNC Drilling

Drilling operations involve creating holes in a workpiece using rotating drill bits. CNC drilling can include:

i. **Center Drilling**: Making small starter holes for accurate deeper drilling.

ii. **Deep Hole Drilling**: Producing deep holes using specialized drills like gun drills.

iii. **Reaming**: Enlarging and smoothing a drilled hole for precision.

iv. **Tapping**: Creating internal threads using a tap tool.

CNC Grinding

Grinding operations improve surface finish and precision. Common types include:

i. **Surface Grinding**: Producing a smooth, flat surface.

ii. **Cylindrical Grinding**: Refining the external and internal diameters of a cylindrical part.

iii. **Centerless Grinding**: Grinding without using centers to hold the workpiece.

CNC Electrical Discharge Machining (EDM)

EDM is a non-traditional machining process that uses electrical sparks to erode material. Types of EDM operations include:

i. **Wire EDM**: Using a thin wire as an electrode to cut intricate shapes.
ii. **Sinker EDM**: Using shaped electrodes to create complex cavities.

CNC Plasma Cutting

Plasma cutting uses a high-temperature ionized gas (plasma) to cut through metals. It is commonly used for cutting thick materials with high precision.

CNC Laser Cutting

Laser cutting employs a focused laser beam to cut materials with extreme precision, used for detailed designs and thin materials.

CNC Waterjet Cutting

Waterjet cutting uses high-pressure water mixed with abrasives to cut materials without heat, making it suitable for delicate materials like composites and glass.

CNC Broaching

Broaching uses a toothed tool to remove material in a linear motion, ideal for cutting keyways, splines, and internal gears.

CNC Honing

Honing is a finishing operation that improves the surface quality and dimensional accuracy of cylindrical parts, commonly used for engine cylinders.

METHODOLOGY: IMPLEMENTATION OF AI IN CNC MILLING

AI integration in CNC milling involves several stages, including data acquisition, real-time monitoring, predictive analytics, and adaptive control. Below is a step-by-step methodology for implementing AI in CNC milling.

Data Acquisition and Preprocessing

AI implementation begins with data collection from various sources such as sensors (measuring temperature, vibration, tool wear), CNC controllers (G-code execution, spindle speed), and machine vision systems (image processing for defect detection). This data undergoes preprocessing, including noise removal, normalization, and feature extraction, ensuring high accuracy in AI-driven decision-making.

AI-Powered Real-Time Process Monitoring

Machine learning algorithms analyze sensor data to detect anomalies and optimize machining parameters. Edge computing enables AI-driven CNC controllers to process data locally for real-time decision-making, while cloud connectivity allows for large-scale data analysis. For instance, if AI detects excessive vibration, it automatically adjusts the spindle speed or feed rate to prevent tool breakage.

Predictive Maintenance Using AI

AI leverages deep learning models to predict tool wear and estimate the remaining tool life based on historical data. Automated alerts notify operators about necessary tool changes before failure occurs, and AI-integrated CNC systems can automatically replace tools, reducing downtime. For example, if AI predicts that a cutting tool will fail after 25 machining cycles, it schedules a replacement at the optimal time.

AI-Based Adaptive Machining Control

AI dynamically adjusts machining parameters such as spindle speed, feed rate, and depth of cut based on real-time feedback. These optimizations improve efficiency and prevent machine damage. For instance, if AI detects chatter during machining, it modifies the spindle speed instantly to stabilize the cutting process.

AI-Driven Quality Control and Inspection

Machine vision technology, powered by AI, inspects surface finish, detects defects, and ensures dimensional accuracy. AI models predict defects before they occur, allowing for corrective actions. Automated quality reports provide real-time assessments, improving decision-making and reducing manufacturing defects.

```python
import numpy as np

# AI-based CNC optimization parameters
spindle_speed = 3000  # Initial RPM
feed_rate = 1200  # Initial feed rate in mm/min
tool_wear = 0  # Initial tool wear (0 = new tool)
max_tool_wear = 10  # Maximum tool wear threshold

# AI-based adjustments (simulated machine learning predictions)
def optimize_machining(spindle_speed, feed_rate, tool_wear):
    if tool_wear > 7:  # If tool wear is high, reduce spindle speed
        spindle_speed -= 200
        feed_rate -= 100
    elif tool_wear > 4:  # If tool wear is moderate, adjust parameters slightly
        spindle_speed -= 100
        feed_rate -= 50
    else:  # If tool wear is low, optimize for efficiency
        spindle_speed += 200
        feed_rate += 100

    return spindle_speed, feed_rate

# Simulating AI-driven CNC milling for 10 cycles
for cycle in range(10):
    tool_wear = np.random.randint(0, max_tool_wear)  # Simulating tool wear
    spindle_speed, feed_rate = optimize_machining(spindle_speed, feed_rate)

    print(f"Cycle {cycle + 1}: Spindle Speed = {spindle_speed} RPM, Feed Rate = {feed_rate} mm/min, Tool Wear = {tool_wear}")
```

Fig. 1: Shown the Algorithm AI Based CNC Optimization

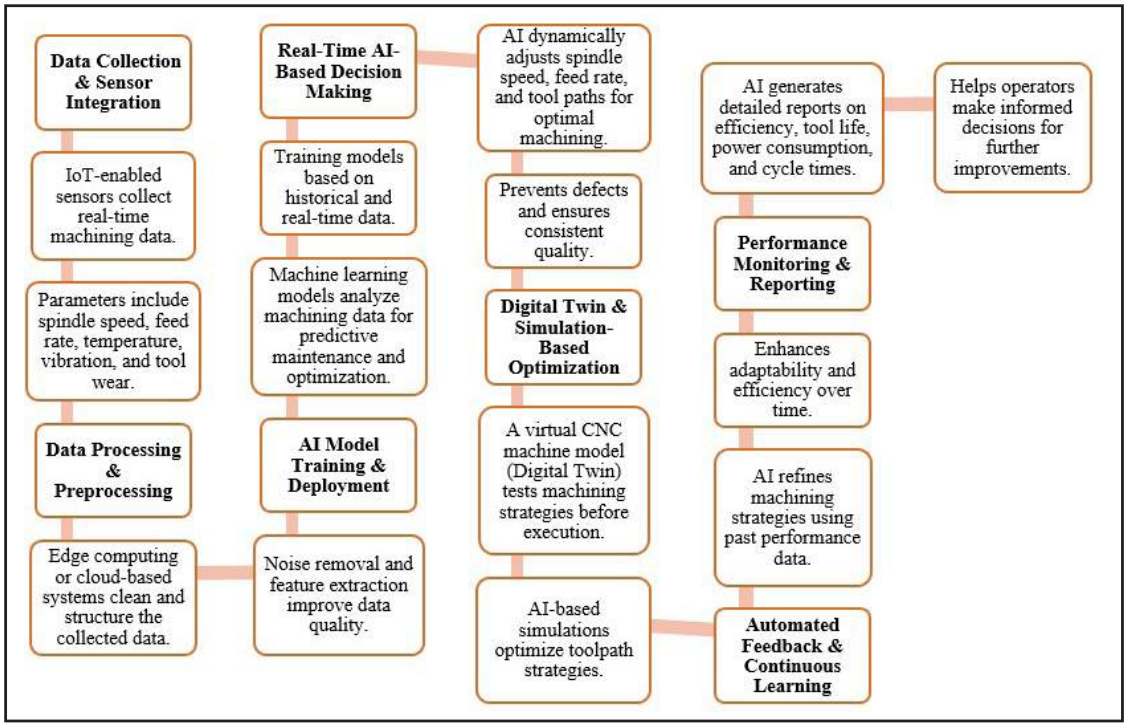


Fig. 2: Shown Flowchart Layout the AI Implementation in CNC Milling

AI Integration with Digital Twin Technology

A digital twin, a virtual replica of the CNC milling process, runs AI-based simulations to optimize tool paths and cutting strategies. AI continuously learns from past machining operations, improving efficiency and reducing errors. For example, AI simulates multiple cutting paths and selects the one that minimizes tool wear while maximizing material removal rates.

ALGORITHM FOR AI-BASED CNC OPTIMIZATION (PYTHON CODE)

Below is a Python algorithm that simulates AI-driven CNC milling optimization. The AI model predicts tool wear and adjusts machining parameters dynamically.

HOW AI HELP TO OPTIMIZE CNC MILLING

AI plays a crucial role in optimizing CNC milling by improving efficiency, precision, and productivity. Below are some key ways AI enhances CNC milling operations:

AI-BASED OPTIMIZATION IN CNC MILLING

The integration of artificial intelligence (AI) in CNC milling has significantly improved efficiency, precision, and productivity. AI-driven technologies enable smart process monitoring, predictive maintenance, adaptive control, tool path optimization, defect detection, automated CAM programming, digital twin technology, and energy efficiency management. These advancements reduce machining time, enhance product quality, and minimize operational costs, making AI an essential component in modern manufacturing (Zhang *et al.*, 2023).

SMART PROCESS MONITORING AND ANOMALY DETECTION

AI-powered sensors and machine learning algorithms facilitate real-time monitoring of machining parameters such as spindle speed, feed rate, tool wear, and vibrations. By continuously analyzing these parameters, AI can detect anomalies early and automatically adjust the machining process to maintain optimal performance. This capability reduces tool wear, prevents costly failures, and improves machining accuracy (Li, Wang, & Chen, 2022).

PREDICTIVE MAINTENANCE FOR ENHANCED RELIABILITY

AI-driven predictive maintenance helps reduce unexpected breakdowns by analyzing historical and real-time machine data to identify potential failures. By scheduling maintenance only when necessary, manufacturers can extend tool and machine lifespan while minimizing unplanned downtime. Research shows that predictive maintenance powered by AI reduces maintenance costs and enhances machine reliability, making it a valuable asset in CNC milling operations (Patel & Kumar, 2021).

ADAPTIVE CONTROL FOR PRECISION MACHINING

Adaptive control systems powered by AI dynamically adjust cutting parameters in response to real-time machining conditions. These systems optimize feed rates, spindle speeds, and depth of cut, resulting in improved surface finish, enhanced dimensional accuracy, and reduced tool wear. AI-based adaptive control has been shown to significantly enhance precision in CNC milling, reducing material waste and increasing production efficiency (Singh *et al.*, 2023).

AI-DRIVEN TOOL PATH OPTIMIZATION

Machine learning algorithms play a crucial role in optimizing tool paths to achieve maximum efficiency. AI analyzes machining strategies to reduce cycle time, improve energy efficiency, and minimize tool deflection and chatter. This optimization leads to higher machining accuracy and reduced wear on cutting tools, ultimately improving the overall manufacturing process (Gupta & Sharma, 2023).

DEFECT DETECTION AND QUALITY CONTROL

AI enhances defect detection and quality control through computer vision and deep learning models. By identifying machining errors in real-time, AI systems reduce rework, scrap rates, and production costs. Advanced AI-driven quality control techniques ensure high precision and consistency in CNC milling operations, improving product reliability (Chen *et al.*, 2023).

AUTOMATED CAM PROGRAMMING

AI-driven Computer-Aided Manufacturing (CAM) software automates the generation of toolpaths and machining sequences, minimizing human intervention. These systems suggest the most efficient cutting strategies, optimize tool selection, and reduce programming time. AI-based CAM automation streamlines CNC milling operations, improving workflow efficiency and reducing errors (Zhao *et al.*, 2022).

DIGITAL TWIN TECHNOLOGY IN CNC MILLING

Digital twin technology, combined with AI, creates virtual models of CNC milling operations to simulate and optimize machining processes before actual production. This approach enables manufacturers to identify potential issues, refine machining parameters, and enhance overall process

Table 1: CNC Milling Before and After AI Implementation

S.No	Parameter	Before AI Implementation	After AI Implementation
1	Process Monitoring	Manual monitoring with periodic inspections.	AI-powered real-time monitoring with sensors and predictive analytics.
2	Tool Wear Detection	Identified after significant degradation.	AI predicts tool wear and suggests preventive actions.
3	Machine Downtime	Frequent due to unexpected failures.	Reduced due to predictive maintenance and early failure detection.
4	Surface Finish	Variability due to manual parameter setting.	Improved consistency with AI-driven adaptive control.
5	Cutting Parameters	Set manually based on operator experience.	AI dynamically adjusts speed, feed rate, and depth for optimal results.
6	Tool Path Optimization	Pre-programmed paths with fixed settings.	AI optimizes paths for minimal tool wear and maximum efficiency.
7	Defect Detection	Manual inspection, often after production.	AI-based real-time defect detection reduces rework.
8	CAM Programming	Time-consuming manual programming.	AI automates toolpath generation and optimizes machining sequences.
9	Energy Consumption	High due to inefficient machining cycles.	Optimized energy use with AI-driven power management.
10	Cycle Time	Longer due to suboptimal processes.	Reduced by AI-based process optimization.
11	Material Waste	Higher due to inconsistent cutting parameters.	Lower due to precise AI-controlled machining.
12	Production Costs	Higher due to tool replacements and rework.	Reduced due to predictive maintenance and defect prevention.

efficiency. Digital twins provide a real-time feedback loop that improves decision-making and reduces material waste (Singh *et al.*, 2023).

ENERGY EFFICIENCY OPTIMIZATION

AI contributes to energy efficiency in CNC milling by adjusting cutting parameters to minimize power consumption and reduce idle time. AI algorithms analyze machine usage patterns and recommend energy-saving measures, leading to lower operational costs and a more sustainable manufacturing process (Gupta & Sharma, 2023).

FORMULAS AND CALCULATIONS FOR AI-BASED CNC MILLING OPTIMIZATION

AI optimizes CNC milling by improving cutting parameters, tool life, energy efficiency, and cycle time.

Material Removal Rate (MRR) Optimization

Material removal rate (MRR) is a key parameter in CNC milling, representing the volume of material removed per unit time. AI optimizes MRR by adjusting feed rate, depth of cut, and spindle speed.

$$MRR = f \times d \times w$$

Where:

f = Feed rate (mm/min)
d = Depth of cut (mm)
w = Width of cut (mm)

AI Optimization:

i. AI continuously monitors **chip load** and **adjusts cutting parameters** to maximize MRR while minimizing tool wear (Zhang *et al.*, 2023).

ii. AI prevents excessive material removal, improving surface quality and tool longevity (Li & Wang, 2022).

Cutting Speed Optimization

Cutting speed (VcV_cVc) affects tool wear, surface finish, and efficiency. AI optimizes cutting speed by analyzing material properties and tool conditions.

$$V_c = \frac{\pi DN}{1000}$$

Where:

Vc = Cutting speed (m/min)

D = Tool diameter (mm)

N = Spindle speed (RPM)

AI Optimization

i. AI **monitors tool condition** and adjusts spindle speed to extend tool life (Gupta & Sharma, 2023).

ii. AI prevents overheating by modifying speed based on **real-time temperature feedback** (Singh *et al.*, 2023).

Feed Rate Optimization

The feed rate (f) determines how fast the tool moves through the material. AI optimizes it for precision and tool life.

$$F = N \times f_z \times Z$$

Where:

f = Feed rate (mm/min)

N = Spindle speed (RPM)

fz = Feed per tooth (mm/tooth)

Z = Number of cutting edges (flutes)

AI Optimization

i. AI **adjusts feed rate in real-time** based on cutting force sensors (Chen *et al.*, 2023).

ii. AI reduces feed when excessive vibrations are detected, improving **machining stability** (Zhao *et al.*, 2022).

Tool Life Optimization (Taylor's Tool Life Equation)

AI optimizes tool life using the **Taylor equation**, which predicts tool wear based on cutting speed.

$$T = CV_c^{-n}$$

Where:

T = Tool life (min)

C = Tool life constant (depends on tool-material combination)

Vc = Cutting speed (m/min)

n = Material-dependent exponent

AI Optimization

i. AI **adjusts spindle speed dynamically** to prevent premature wear (Patel & Kumar, 2021).

ii. AI schedules **predictive maintenance** by analyzing tool degradation trends (Li *et al.*, 2022).

Energy Consumption Optimization

AI improves energy efficiency by optimizing machining parameters and reducing idle time.

$$E = P \times t$$

Where:

E = Energy consumed (kWh)

P = Power consumption (kW)

t = Machining time (hours)

AI Optimization

- AI **reduces unnecessary spindle operation** by analyzing usage patterns (Gupta & Sharma, 2023).
- AI **minimizes power spikes** by controlling feed rate and depth of cut (Zhao *et al.*, 2022).

Machining Time Reduction

AI minimizes machining time by optimizing tool paths and cutting strategies.

$$t_m = \frac{L}{f}$$

Where:

tm = Machining time (min)

L = Total length of cut (mm)

f = Feed rate (mm/min)

AI Optimization

i. AI **chooses shortest tool paths**, reducing machining time by 15-20% (Singh *et al.*, 2023).

Table 2: CNC Milling Performance Before and After AI Optimization

S.No	Parameter	Before AI Optimization	After AI Optimization	Improvement (%)
1	Spindle Speed (RPM)	3000	3200	+6.67%
2	Feed Rate (mm/min)	1200	1440	+20%
3	Depth of Cut (mm)	2	2.5	+25%
4	Width of Cut (mm)	4	4	No Change
5	Material Removal Rate (MRR) (mm^3/min)	9600	14400	+50%
6	Tool Life (min)	19.6	22.4	+14.3%
7	Cutting Speed (m/min)	94.2	100.5	+6.7%
8	Machining Time (min)	10	8	-20%
9	Energy Consumption (kWh)	2.5	2.0	-20%

ii. AI **prevents unnecessary tool retractions**, improving efficiency (Chen *et al.*, 2023).

CALCULATION: BEFORE AND AFTER AI OPTIMIZATION

Given Data:

i. Spindle speed (N) = 3000 RPM

ii. Tool diameter (D) = 10 mm

iii. Feed per tooth (fz) = 0.1 mm/tooth

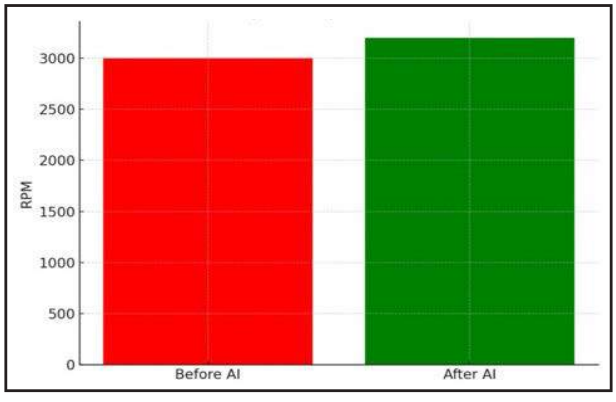
iv. Number of cutting edges (Z) = 4

DETAILED OUTCOME RESULT WITH IMPACT OF AI OPTIMIZATION IN CNC MILLING

The bar graph provides a visual comparison of various machining parameters before and after AI optimization. Below is a detailed breakdown of how AI improves CNC milling performance in different aspects.

Spindle Speed Enhancement

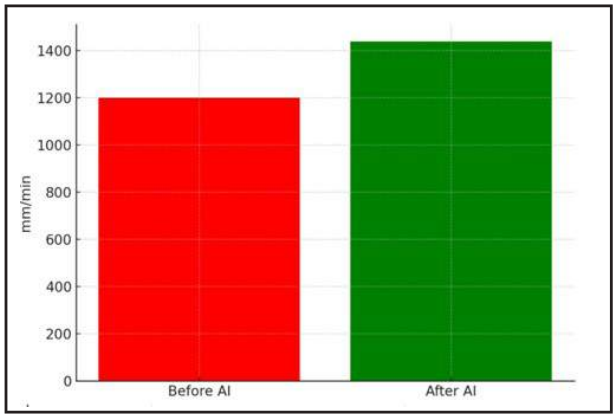
- **Before AI:** Spindle speed was 3000 RPM, and the feed rate was 1200 mm/min.
- **After AI:** AI dynamically adjusted spindle speed to 3200 RPM (+6.67%) and increased the feed rate to 1440 mm/min (+20%).
- **Impact:** These changes result in a smoother cutting process, reducing vibrations and improving tool life.



Graph 1: Spindle Speed (RPM)

Feed Rate Enhancement

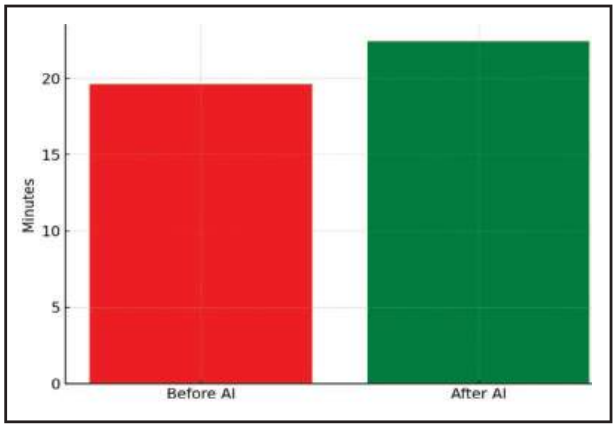
- **Before AI:** 1200 mm/min
- **After AI:** 1440 mm/min (+20%)
- **Effect:** A higher feed rate allows for faster material removal, increasing overall efficiency.



Graph 2: Feed Rate (mm/min)

Tool Life Improvement

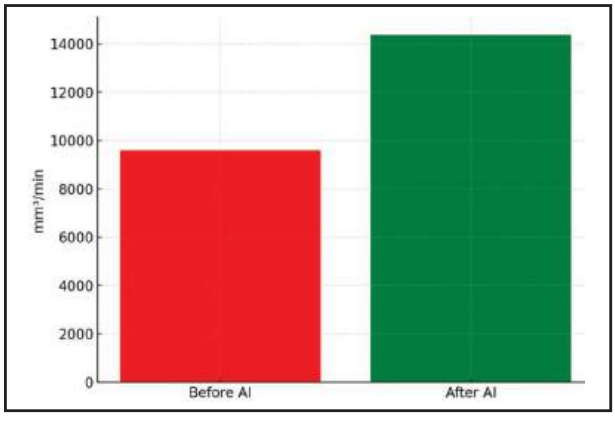
- **Before AI:** 19.6 minutes
- After AI: 22.4 minutes (+14.3%)
- **Effect:** AI-based monitoring reduces excessive tool wear, extending the lifespan of cutting tools.



Graph 4: Tool Life (min)

Material Removal Rate (MRR) Improvement

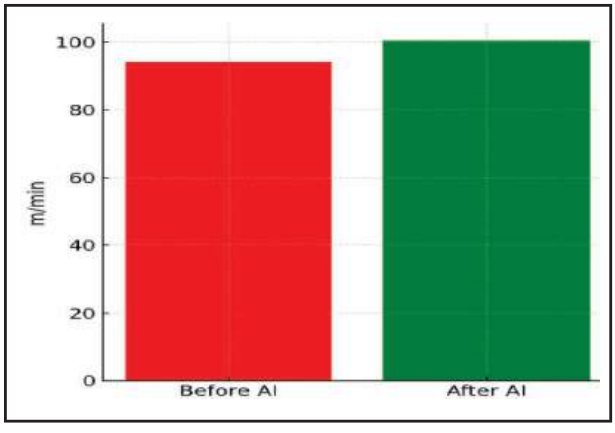
- Before AI: 9600 mm^3/min
- After AI: 14400 mm^3/min (+50%)
- **Effect**: AI optimizes feed rate and depth of cut, significantly improving material removal rates.



Graph 3: MRR (mm^3/min)

Cutting Speed Optimization

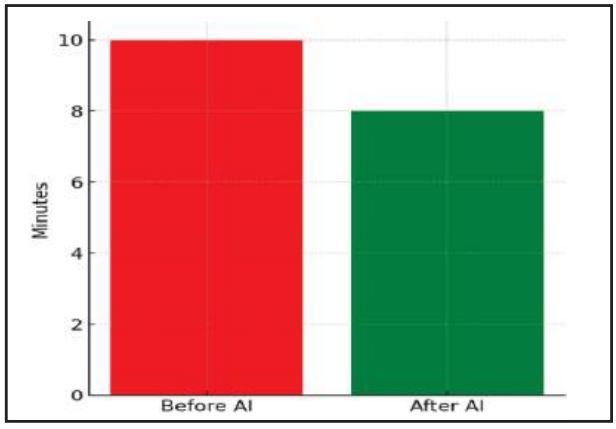
- **Before AI:** 94.2 m/min
- **After AI:** 100.5 m/min (+6.7%)
- **Effect:** AI optimizes speed to ensure efficient cutting while minimizing thermal stress.



Graph 5: Cutting Speed (m/min)

Machining Time Optimization

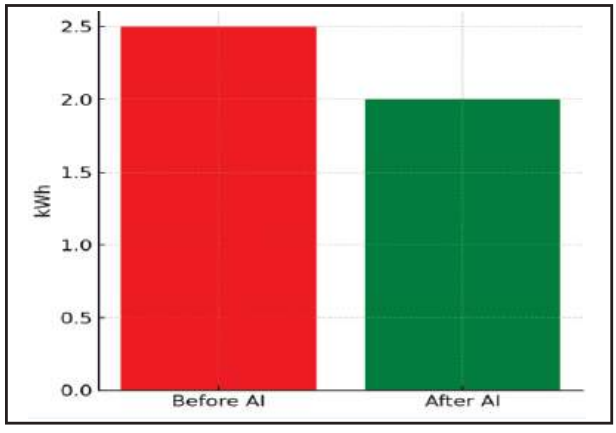
- **Before AI:** 10 minutes
- **After AI:** 8 minutes (-20%)
- **Effect:** AI-driven process optimization reduces idle time, increasing productivity.



Graph 6: Machining Time (min)

Energy Consumption Optimization

- **Before AI:** 2.5 kWh
- **After AI:** 2.0 kWh (-20%)
- **Effect:** Lower machining time and optimized power usage reduce overall energy consumption, making the process more sustainable.



Graph 7: Energy Consumption

RESULTS

The implementation of AI in CNC milling has significantly improved machining efficiency and precision. Key performance metrics before and after AI integration are summarized in the table 3 below

The results indicate a significant enhancement in MRR, tool life, machining time, and energy efficiency due to AI-driven process optimization, real-time adjustments, and predictive maintenance. The surface finish has also improved, reducing the need for secondary finishing operations.

CONCLUSION

AI-based process monitoring and control in CNC milling have proven to be **highly effective in optimizing machining performance**. By leveraging **machine learning, real-time sensor feedback, and digital twin simulations**, AI enables **dynamic adjustments in spindle speed, feed rate, and tool wear management**. The study confirms that AI integration leads to:

i. **Higher productivity** through increased MRR and reduced machining time.

ii. Lower operational costs by extending tool life and reducing energy consumption.

iii. Improved product quality with enhanced surface finish and defect minimization.

iv. Sustainable machining practices by optimizing energy utilization and minimizing waste.

Overall, AI transforms CNC milling into a more intelligent, adaptive, and cost-effective manufacturing process.

DISCUSSION

The improvements observed in this study can be attributed to AI's ability to analyze real-time data, predict anomalies, and make autonomous process adjustments. Traditional CNC machining relies on pre-set machining parameters, which often lead to inefficiencies due to varying cutting conditions. AI, on the other hand:

i. **Adapts in real-time**, ensuring **optimal cutting conditions** even for complex geometries and materials.

ii. **Predicts tool wear** and schedules maintenance **before failures occur**, reducing downtime.

iii. **Uses digital twins** to simulate multiple machining strategies, selecting the most **efficient toolpaths.**

Table 3: Comparison of CNC Milling Performance Before and After AI Implementation

S.No.	Parameter	Before AI Implementation	After AI Implementation	Improvement (%)
1	Material Removal Rate (MRR)	0.8 cm^3/min	1.2 cm^3/min	+50%
2	Tool Life (Cycles)	70	80	+14.3%
3	Machining Time (min)	50	40	-20%
4	Energy Consumption (kWh)	5.0	4.0	-20%
5	Surface Finish (Ra, µm)	1.2	0.8	+33.3%

Despite these advantages, AI implementation in CNC milling **requires high computational power, initial setup investment, and skilled personnel** to manage AI models. Additionally, **real-time AI integration with legacy CNC machines** may require modifications or additional hardware.

FUTURE SCOPE

AI in CNC milling is still evolving, and several areas offer **scope for further research and improvements**:

i. Advanced AI Algorithms for Adaptive Machining
ii. Integration of IoT and Edge Computing
iii. AI-Powered Autonomous CNC Systems
iv. Sustainability and Green Manufacturing
v. Human-AI Collaboration in Smart Factories

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Exploring Factors Affecting Land Surface Temperature Using Machine Learning Technique: A Case Study on Meghalayan Terrain

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Abstract—Earth's surface temperature continues to rise steadily over time. A Long-term assessment of Earth's Land Surface Temperature (LST) trend and changes in land use/land cover (LULC) can help understand its cause and effect on the environment. This study aims to use LST trend and LULC change information to analyze its impact on the state of Meghalaya. As an indicator, the trend in LST is used to examine the effects of natural and human-induced activities, supported by the decadal land use change assessment. The study utilizes a Mann-Kendall test to identify the trend in LST from the last 22 years (2000–2021). Similarly, a machine learning technique (Random Forest) is used to analyze the dynamics of decadal LULC change. Inter class differences in conjunction with LST trends are then cross-validated to draw any conclusion. The test suggests an increasing trend in LST for the Meghalayan region. Corresponding analysis of LULC change suggests that the conversion of vegetation land to buildup areas rose from 28% in 2000-2010 to 45% in 2010-2021. Similarly, 20% of forest land was converted to buildup areas in the first half, with a slight decrease to 14% in the second half. Furthermore, the importance of temperature, rainfall, and DEM in modelling LST variations was also outlined as a part of the parameter importance analysis performed in this study. By utilizing these insights and methodology, effective measures can be developed to counter the harmful effects of deforestation and urbanization, thus preserving the ecological balance of our ecosystems for future generations.

Keywords: Land surface temperature, LULC change, Mann-Kendall test, environmental impact, Meghalaya.

INTRODUCTION

Increasing Earth's surface temperature has become a global issue. It is estimated that the Earth's surface temperature is expected to increase by ~0.2°C per decade with an additional increase of 1.8°C to 4.0°C by the end of this century (Staszewski, 2023; Zheng *et al.*, 2022).This can cause significant environmental stress, driven by population growth, unplanned urbanization, industrialization, and deforestation. With the rising global population, the demand for resources will also increase. This will ultimately lead to the degradation of natural resources and put additional pressure on our ecosystem (Gondwe *et al.*, 2021; Hossain *et al.*, 2023; Sajan *et al.*, 2023).

This article presents a case study of Meghalaya, a north-eastern state of India. The region's extensive forest cover is a sanctuary for numerous endangered species, making it a vital ecological hotspot. However, the state has undergone notable changes in its LULC forms, particularly in its rich vegetation and forested areas (Singh *et al.*, 2020). Human encroachment of forest areas poses a grave threat, resulting

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in the loss of invaluable forest resources and habitat degradation. These transformations have significantly impacted the region's ecological balance, exerting deep effects on the livelihoods of nearly 81% of the total population who rely heavily on forests for sustenance and cultural practices.

The literature survey reveals it's a fact that LULC and LST have a strong correlation and temperature rise has often been subjugated to transformation from natural vegetated areas into the built-up class (Moisa *et al.*, 2022). There are multiple studies specifically done to investigate LST and LULC changes for observing variations in local temperature for a given region (Ezimand *et al.*, 2024; Vohra *et al.*, 2024). Existing studies primarily used remote sensing imageries to analyze changes in surface temperature by utilizing LULC and Thermal Field Variance Index (TFVI) maps. In addition, researchers have extensively explored the use of various land cover spectral indices, such as the Normalized Difference Vegetation Index (NDVI), Normalized Difference Bareness Index (NDBaI), and the Normalized Difference Buildup Index (NDBI) in delineating different LULC classes.

Human activities, such as burning fossil fuels, have released greenhouse gases that can trap the sun's heat and cause global warming. Consequently, nearly all land areas are experiencing increasingly hotter days. For instance, 2020 ranked among the hottest years ever recorded. LST serves as an important indicator of ecosystem health. Elevated temperature creates stress on the ecosystems (e.g., droughts and heat waves) (Zhang *et al.*, 2023). It can worsen environmental conditions, reducing biodiversity, causing ecosystem degradation, and increasing vulnerability to disturbances (Rogers-Bennett and Catton, 2022). Moreover, surface temperature influences various ecosystem processes, including photosynthesis, evapotranspiration, and nutrient cycling. Temperature changes can disrupt these processes, affecting ecosystem productivity, water availability, and nutrient dynamics (Duan *et al.*, 2022). By tracking surface temperature, scientists can assess how ecosystems respond to changing environmental conditions and predict potential ecological patterns and function shifts. Also, LST monitoring enables the implementation of adaptive management strategies to mitigate potential impacts and promote ecosystem resilience. Factors that affect LST are equally important. Multiple studies have shown that the Digital elevation model (DEM) and the normalized difference vegetation index (NDVI) have a strong correlation with surface temperature (Feng *et al.*, 2019; Ham *et al.*, 2022). In addition, the Normalized Difference Built-Up Index (NDBI) is also found to be positively correlated with LST (Saha *et al.*, 2024). In this study, we have considered temperature, rainfall, DEM, u-component of wind, v-component of wind, pressure, and NDVI to predict the LST of Meghalaya.

Likewise, the Land Use Land Cover (LULC) also plays a crucial role in understanding various aspects of our environment. Studies have shown that LST variations can be determined by analyzing the LULC change (Guha, 2021; Keerthi Naidu and Chundeli, 2023; Sajan *et al.*, 2023). LULC maps, derived from satellite imagery and ground surveys are some of the credible sources to provide valuable insights into the patterns of LST and land use changes. By analyzing LULC maps, we can identify signs of deforestation, urbanization, and agricultural expansion in a region. This information is crucial for understanding the influence of human activities on the environment and develop strategies for sustainable land management. Furthermore, LULC maps offer critical insights into vegetation health, changing patterns, and urbanization trends. They help identify areas of concern, such as degraded ecosystems or expanding urban areas, allowing policymakers to prioritize conservation and land-use planning initiatives.

Despite this issue's critical importance, only a few number of studies have been carried out on Meghalaya's persistent LULC transformation processes and the factors driving these changes (Bhuyan *et al.*, 2023; Lamare *et al.*, 2019; Prokop, 2020). Moreover, these studies did not consider LST in consideration, which is a direct indicator of global warming. In this study, we wish to develop a comprehensive framework by incorporating LST and LULC change to address this problem. It will help us to understand the kind of environmental stress the region is facing and the factors responsible for bringing this change.

Recent advancements in RS/GIS technology have made it easier to analyze and monitor environmental changes (Chughtai *et al.*, 2021; Kanagasundaram *et al.*, 2022). These powerful tools provide capabilities for processing and interpreting geospatial information (Kaur *et al.*, 2023). Additionally, the availability of geospatial repositories further enhances accessibility to a vast array of satellite imagery and other geospatial datasets, facilitating research, decision-making, and innovation across various domains. Many recent studies have used Google Earth Engine (GEE) to perform complex geospatial analyses without the need for extensive computational resources or specialized software (Sajan *et al.*, 2023). By leveraging Google's infrastructure, users can process large-scale environmental data efficiently and extract valuable insights into land cover, land use, vegetation dynamics, climate change, and more.

Based on our literature survey, we hypothesize that the increase in land surface temperature is driven by changes in Land Use and Land Cover (LULC), subsequently affecting biodiversity. To validate this hypothesis, we have outlined the following objectives:

- **Objective 1:** To analyze the changes in LULC practices for the state of Meghalaya using high-satellite imagery from the last22 years (2000–2021).
- **Objective 2:** To analyze the trend in LST from 2000 to 2021 and develop a model to capture the relationship between LST and its affecting factors. Subsequently, determine the relative importance of each constituent attribute.

The manuscript is organized into five sections to enhance readability. Section 2 provides an overview of the study area and the methodologies used in the data acquisition, classification, prediction, evaluation, and trend analysis. In Section 3, the results obtained from these various methods are presented. Section 4 delves into a detailed discussion of the findings and their broader significance. Finally, Section 5 encapsulates the key insights and implications of the study as the concluding remarks.

MATERIALS AND METHOD

Study Area

We have selected the state of Meghalaya as a case study because of recent developments in the name of industrialization and other expansion activities (Chakraborty and Saikia, 2022). Moreover, as per the latest Sustainable Development Goal (SDG) India Index 2023-2024 report, the state finds itself among the least performing states and union territories. The study area extends from latitude 24°58' to 26°07'N and longitude 89°48' to 92°51'E, as depicted in Fig. 1. Meghalaya ranks among the wettest regions globally, with high annual rainfall attributed to its steep terrain and proximity to the Bay of Bengal. Cherrapunji and Mawsynram in Meghalaya hold the record for the highest yearly rainfall in the world (Bhuyan *et al.*, 2023; Chakraborty and Saikia, 2022). The temperature fluctuates across the region, with the central highlands experiencing 2 to 24 °C and the western half ranging from 12 to 33 °C (Suri *et al.*, 2023).

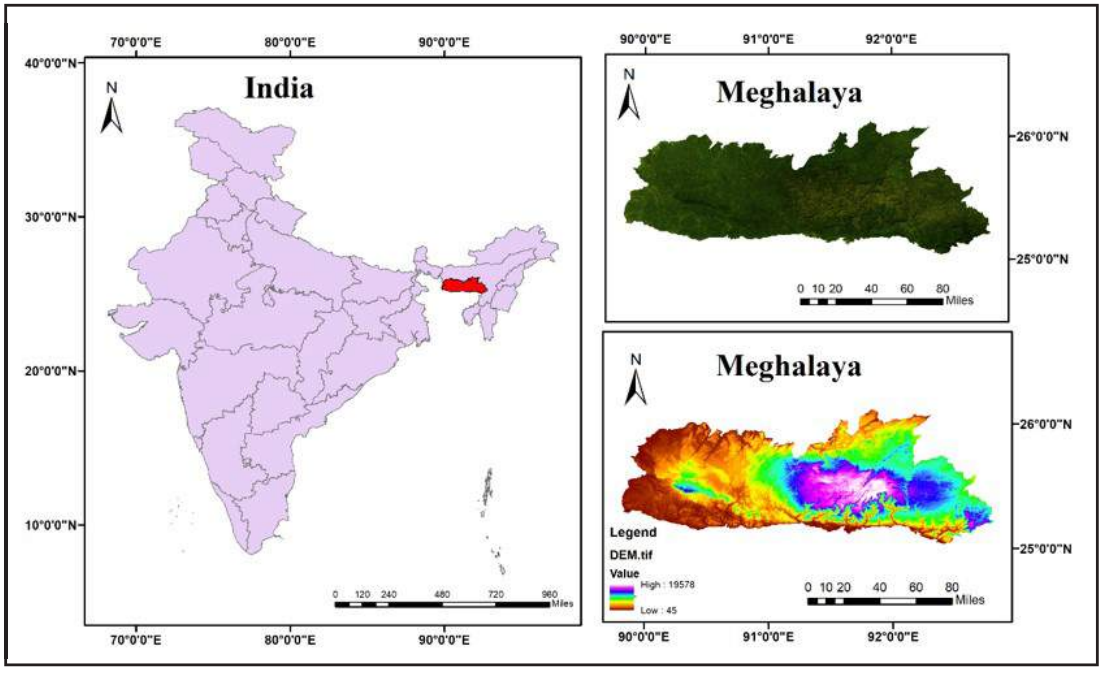


Fig. 1: Study Area Map

In recent decades, rapid urbanization in Meghalaya has exerted considerable pressure on the natural environment and initiatedvarious infrastructure development projects. This has resulted in reduced vegetation cover, loss of water bodies, and alterations in drainage systems. Over this period, Meghalaya's population has surged by 27.95%, rising from 2.32 million

(23.19 lakhs) to 2.97 million (29.67 lakhs) (Census of India data 2011) (Keerthi Naidu and Chundeli, 2023) .

Data Collection

Landsat 7 satellite images with a spatial resolution of 30 meters by 30 meters from the years 2000, 2010, and 2021 were acquired using Google Earth Engine. These images were selected to examine Land Use and Land Cover (LULC) changes for the specified timeframe. To ensure data accuracy, cloud-free images from November to December timeline were specifically chosen. The deliberate exclusion of cloud cover improves visibility and maintains the precision of the study.

The study was conducted in multiple steps. These steps include data preprocessing, feature collection, LULC classification, accuracy assessment, calculation of LST trend, and the analysis of the factors affecting LST. Fig 2 presents the workflow diagram of the study.

To minimize data preprocessing time and to ensure a likeness, the GEE cloud-based platform was used. With ample satellite imaginary and geospatial datasets available in this platform, it merges geospatial datasets using JavaScript and makes computational processing on satellite images easier (Kaur *et al.*, 2023). Several preprocessing steps were taken in this study including copy raster, mosaic to a new raster with all bands, and extract by mask.

For cloud and shadow masking the "pixelqa" band of Landsat-7and the Band Quality Assessment (BQA) function were used. The cloud confidence bit of pixelqa band less than 3 was considered as good pixels and those having confidence bit equal to 3 or more were considered as bad pixels. These identified "bad" pixels are then masked from the image, ensuring that only clear-sky pixels are retained. Finally, edge pixels were removed from all bands to refine the quality of the resulting image.

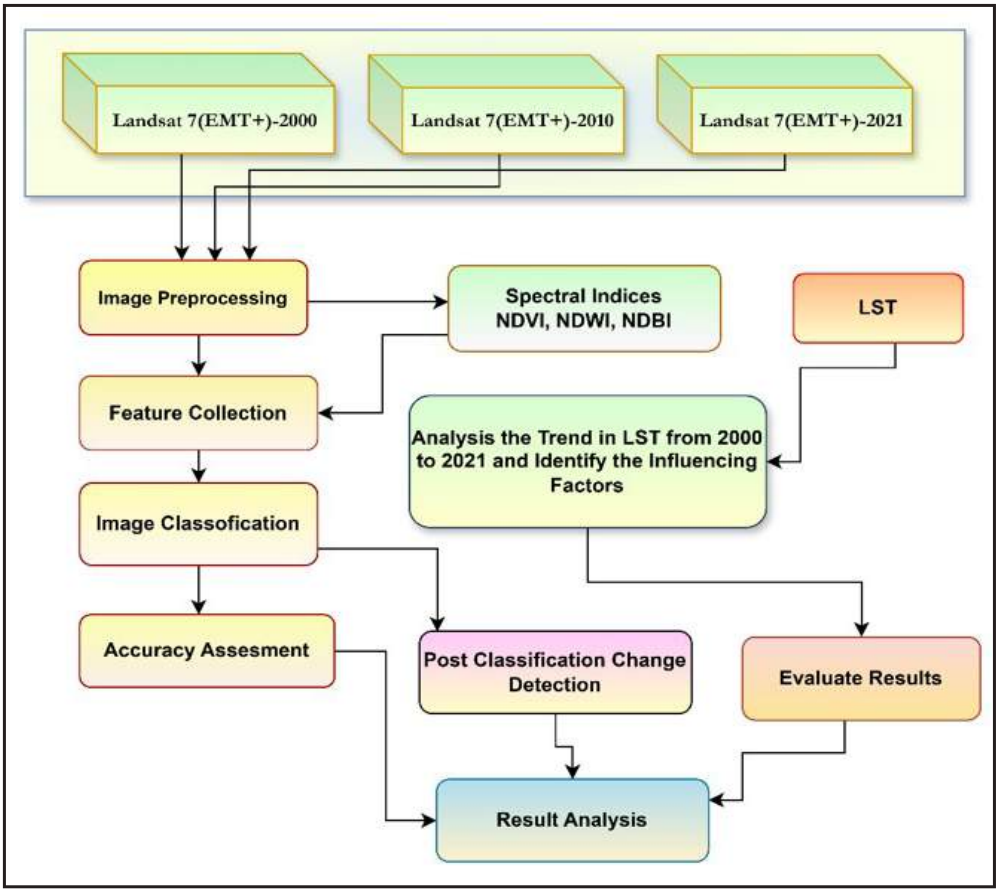


Fig. 2: Schematic Framework of the Methodology

Feature Selection

After the pre-processing stage, feature selection was carried out. Spectral indices such as NDVI (Normalized Difference Vegetation Index), NDWI (Normalized Difference Water Index), and NDBI (Normalized Difference Built-up Index) were calculated. These indices offer valuable insights into vegetation cover, water bodies, and built-up areas, respectively (Bhuyan *et al.*, 2023; Keerthi Naidu and Chundeli, 2023). By incorporating these spatial indices alongside standard band values, it is possible to capture the spectral features and enhance the model's accuracy.

Normalized Difference Vegetation Index (NDVI)

The NDVI is a useful tool for analyzing vegetation growth, monitoring changes in land cover, and researching the effects of environmental conditions on plant health.

$$NDVI = \frac{(NIR - \text{Red})}{(NIR + \text{Red})}$$

Here, NIR stands for near-infrared light reflectance and red stands for red light reflectance. Typically, reflectance measurements are obtained from satellite or aerial images. The resultant NDVI values vary from -1 to +1. Higher positive numbers imply thick and healthy vegetation, whereas lower or negative values indicate a lack of vegetation or a low vegetation density (Huang *et al.*, 2021).

Normalized Difference Water Index (NDWI)

NDWI stands for Normalized Difference Water Index. It is a spectral index used in remote sensing to identify and observe the presence of water bodies (Gao, 1995).

$$NDWI = \frac{(NIR - \text{SWIR})}{(NIR + \text{SWIR})}$$

Here, NIR represents the reflectance of near-infrared light, and SWIR represents the reflectance of shortwave infrared light. NDWI values vary from -1 to +1, with greater positive values indicating higher water concentrations and lower or negative values indicating non-water features (Gao, 1996). NDWI is frequently used to map and monitor water bodies such as lakes, rivers, and wetlands and to measure changes in water content over time.

Normalized Difference Built-Up Index (NDBI)

The Normalized Difference Built-Up Index (NDBI) is a spectral index used in remote sensing to detect and map built-up areas or urbanized regions (Zha *et al.*, 2003). NDBI compares the reflecting intensity of NIR and SWIR light wavelengths to determine the relative abundance of built-up or man-made materials within a given area.

$$NDBI = \frac{(SWIR - NIR)}{(SWIR + \text{NIR})}$$

NDBI values span from -1 to +1, where positive values close to 1 indicate built-up areas, such as buildings and roads, while low values close to -1 represent non-built-up areas, such as vegetation or bare soil. NDBI is mainly used for urbanization monitoring, land use planning, and urban growth analysis.

LULC Classification

After collecting the features, the next phase in the LULC change study is the classification of Landsat images. Classification is a procedure that uses spectral properties to assign pixels in a view to distinct land cover classes (Amini *et al.*, 2022). In this particular study, a machine learning classifier, Random Forest, has been employed for the classification task. It is works on the decision tree principle, with numerous decision trees integrated to produce an ensemble model (Ho, 1995). Each decision tree in the random forest is trained on an arbitrary portion of the training data and makes judgments using a random subset of features (Fratello and Tagliaferri, 2018). This randomization adds variation to the trees, lowering the danger of over-fitting and increasing the model's overall performance.

Random Forest can handle categorical and continuous variables, making it well-suited to the wide variety of data types commonly encountered in LULC datasets. Second, it can handle high-dimensional data successfully, supporting many input variables or features commonly seen in LULC datasets, such as spectral bands, indices, and texture measures. Furthermore, Random Forest resists noisy and correlated input variables, which is useful when working with remotely sensed imagery data susceptible to various noises and artifacts. Different Land cover classes identified in this study are presented in Table 1.

Table 1 : LULC Class Description

LULC class	*Description*
Water	This class comprises lakes, rivers, ponds, and reservoirs, which serve as important habitats for aquatic organisms and as a significant water supply.
Forest	This class includes open forests, dense forests, and big plantations, each indicating a different level of tree cover density and type of wooded region.
Vegetation	This category includes non-forest vegetation such as grasslands, shrubs, cultivated crops, and other types of plants.
Barren Land	Areas with little or no vegetation, such as deserts or stony terrains, have low ecological production.
Built-Up area	Comprises urban or developed areas with infrastructure, buildings, roads, and human settlements.

Data accuracy is crucial for processing and analyzing classified remote sensing data. The accuracy assessment used a confusion matrix to evaluate errors across five natural and man-made feature classes. Confusion matrix, the Overall Accuracy (OA) and the Kappa Statistic were calculated to validate the LULC classification results (Cohen, 1960; Pearson, 1904). Equation 4 is used to calculate the overall accuracy. Here, TP is the true positive, TN is the true negative, FP is the false positive, and FN represents the false negative value. Equation 5 is used to calculate the kappa coefficient. Here, Observed is $\frac{TP + TN}{N}$, and the calculation of random value shown in Equation 3. p1, p2 are calculated with Equation 1 and Equation 2, respectively.

$$p1 = \frac{TP + FP}{N} * \frac{TP + FN}{N} \quad (1)$$

$$p1 = \frac{FN + TN}{N} * \frac{FP + TN}{N} \quad (2)$$

$$Random = p1 + p2 \quad (3)$$

$$Overall\ Accuracy = \frac{TP + TN}{TP + TN + FP + FN} \quad (4)$$

$$kappa = \frac{Observed - Random}{1 - random} \quad (5)$$

Post-classification Change Detection

Change detection is a method that identifies a feature or phenomenon by examining it at its characteristic time (Afaq and Manocha, 2021), also defined as a technique of identifying geographical changes from Geographic Information System (GIS) data as a result of natural or artificial events. Change detection is vital for observing ecosystem changes, changes in land use and land cover, and land mapping changes (Shah *et al.*, 2023). Examining environmental conditions, such as consequences of natural disasters and urban growth, identifying changes in agriculture, assessing deforestation, and identifying specific urban or natural variances in the ecosystem, is usually done through LULC detection. Following the study of LULC using remote sensing data from the years 2000, 2010, and 2021 of Meghalaya, the next stage is to discover changes from 2000 to 2010 and 2010 to 2021. In this study, the QGIS SCP plugin was used to generate the change detection map for these periods. The objectives of change detection are to identify and measure changes in land cover classes over different timescales. Analyzing variations between 2000 and 2010 exposes previous LULC dynamics while evaluating changes between 2010 and 2021 indicates more recent trends. Change detection helps to monitor the environment, inform land management policies, and facilitate decision-making for sustainable land use practices (Jiang *et al.*, 2022).

LST trend and Factors Affecting the Trend

LST has emerged as a critical indicator for analyzing and interpreting the Earth's surface's thermal dynamics with vegetation changes and associated climatic events (Hossain *et al.*, 2023). From 2000 to 2021, the lowest and maximum temperatures in Meghalaya grew considerably, rising from 15.33°C to 20.25°C and 31.61°C to 35.81°C, respectively, as observed from LST data. Mann-Kendall (MK) test was performed to analyze the LST trend of Meghalaya. The MK test is a non-parametric statistical test that uses time series data to detect trends (Hamed and Ramachandra Rao, 1998). The output of the test contains h, p, tau, and slope. '*h*' represents the hypothesis test result; it indicates any significant trend present in data. '*p*' represents the probability of observing if the null hypothesis is true. '*Tau*' also known as Kendall's Tau represents the strength and direction of data. '*Slope*' represents magnitude; it represents the rate of change of a variable over time.Surface reflectance Landsat 7 ETM+ imaginary dataset is used to collect the LST data of Meghalaya.

Urban areas, known for their substantial solar radiation absorption, have higher LST. Vegetation or water regions, on the other hand, have lower LST values due to solar radiation scattering, plant heat absorption, and transpiration (Sajan *et al.*, 2023). The LST is influenced by various factors, including the Digital Elevation Model (DEM), NDVI, eastward and westward components of 10m wind, pressure, temperature, and rainfall. The DEM, which represents the land's topography, can impact LST due to its influence on local air circulation patterns and the exposure of different surfaces to solar radiation. NDVI is a measure of vegetation density. Wind components, particularly the eastward and westward components at 10m height, can influence LST by affecting air flow and heat transfer across the surface. Variations in pressure contribute to changes in atmospheric conditions, which in turn impact the LST. Finally, rainfall can cool down the land surface by reducing solar heating and changing moisture content. A total of 2,772 data points were generated using the Fishnet feature of ArcGIS for data collection purposes (ESRI, 2016). These components work together to determine the complex dynamics of LST, providing insights into the thermal behavior of the Earth's surface across different landscapes. To understand the relationship a random forest-based predictive model was fit and a variable of importance matrix was computed. The fitness of the model and the prediction accuracy were evaluated with R-square and RMSE values.

RESULTS

We have used Landsat-7 images to analyze the changes in LULC for the state of Meghalaya. The LULC map of Meghalaya is classified into five classes, viz. forest, water, vegetation, barren land, and build for the years 2000, 2010, and 2021. LULC map is a good reporter of different land cover types, monitoring changes over time and assessing the impact of human activities or natural phenomena on the landscape. We hypothesized that the depletion of vegetation or forest land would result in higher land surface temperatures. In this regard, our first step is to create a LULC map of Meghalaya for the years 2000, 2010, and 2021 (Fig. 3).

Table 2: Presents the Total area of Each Land Cover Class in Meghalaya, Represented in Square Kilometers (km^2) and as a Percentage (%), for the Years 2000, 2010, and 2021:

Class	Land cover 2000		Land cover 2010		Land cover 2021	
	Area (Km^2)	(%)	Area (Km^2)	(%)	Area (Km^2)	(%)
Water	358.90	1.60	225.91	1.01	111.20	0.50
Forest	19126.91	85.34	18195.67	81.18	18880.62	84.26
Vegetation	1968.11	7.57	2958.23	13.18	2635.29	11.76
Barren Land	1197.84	5.34	960.56	4.29	56.80	0.25
Build up	18.43	0.08	59.63	0.27	716.09	3.19
Total	22400	100	22400	100	22400	100

Table 3: Represent user Accuracy, Producer Accuracy, Kappa, and Overall Accuracy of the Random Forest Algorithm for the Years 2000, 2010, and 2021.

	Class	2000				2010				2021			
		User Accuracy	Producer Accuracy	Kappa	Overall Accuracy	User Accuracy	Producer Accuracy	Kappa	Overall Accuracy	User Accuracy	Producer Accuracy	Kappa	Overall Accuracy
RF	Water	0.94	0.92	0.95	0.98	0.98	0.96	0.97	0.98	0.79	0.90	0.81	0.87
	Forest	0.99	0.99			0.98	0.99			0.96	0.91		
	Vegetation	0.98	0.95			0.95	0.96			0.63	0.68		
	Barren	0.94	0.92			0.97	0.96			0.79	0.94		
	Build up	0.98	0.88			0.96	0.99			0.93	0.77		

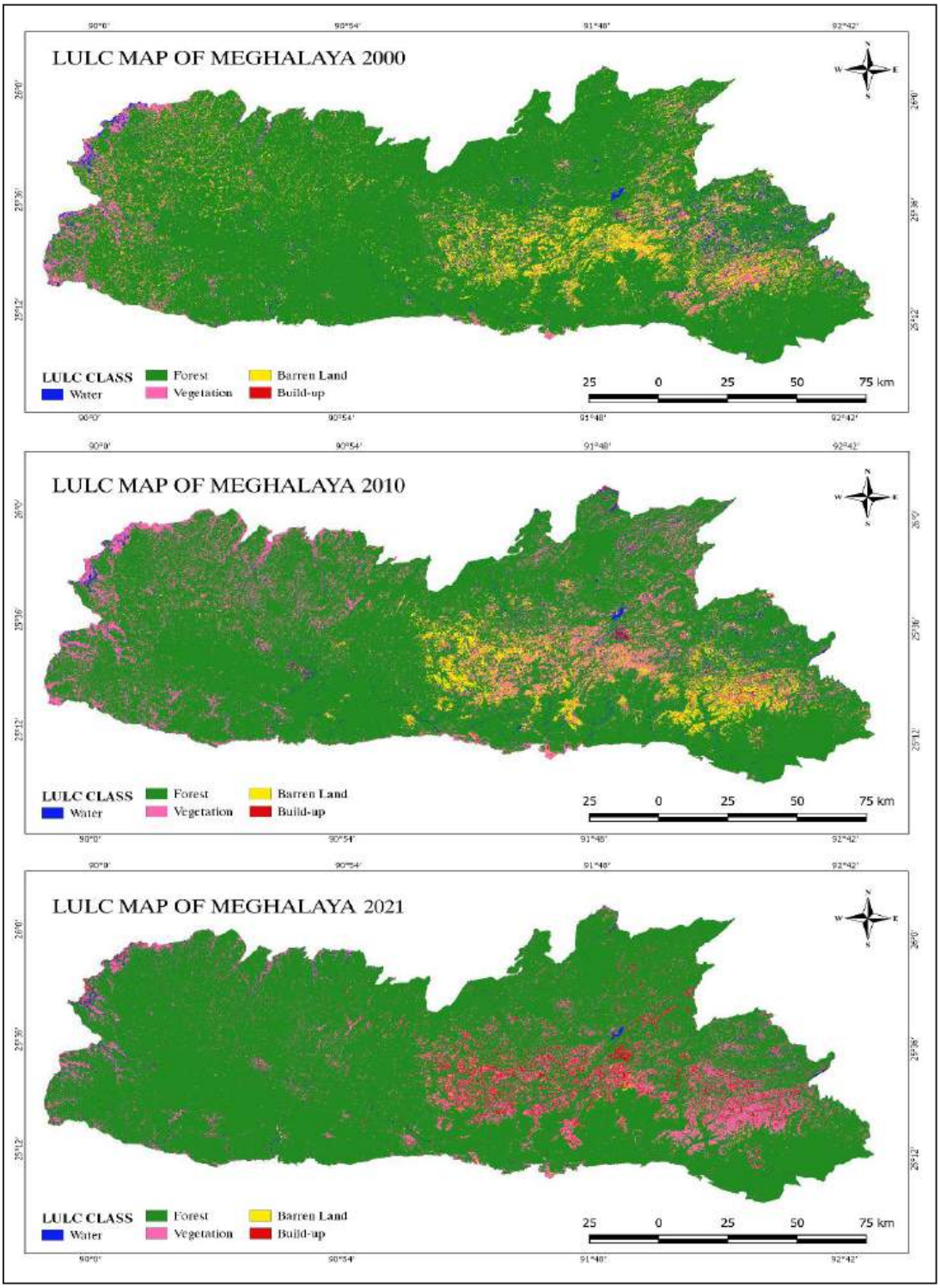
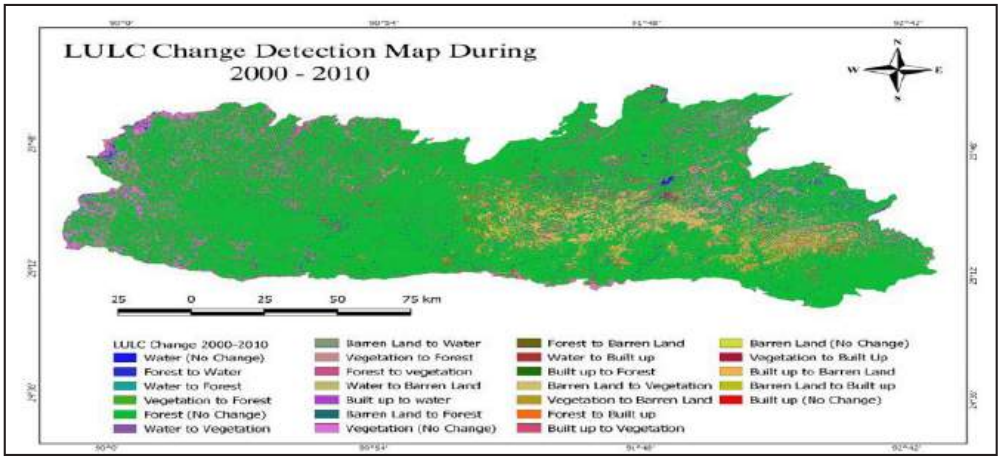
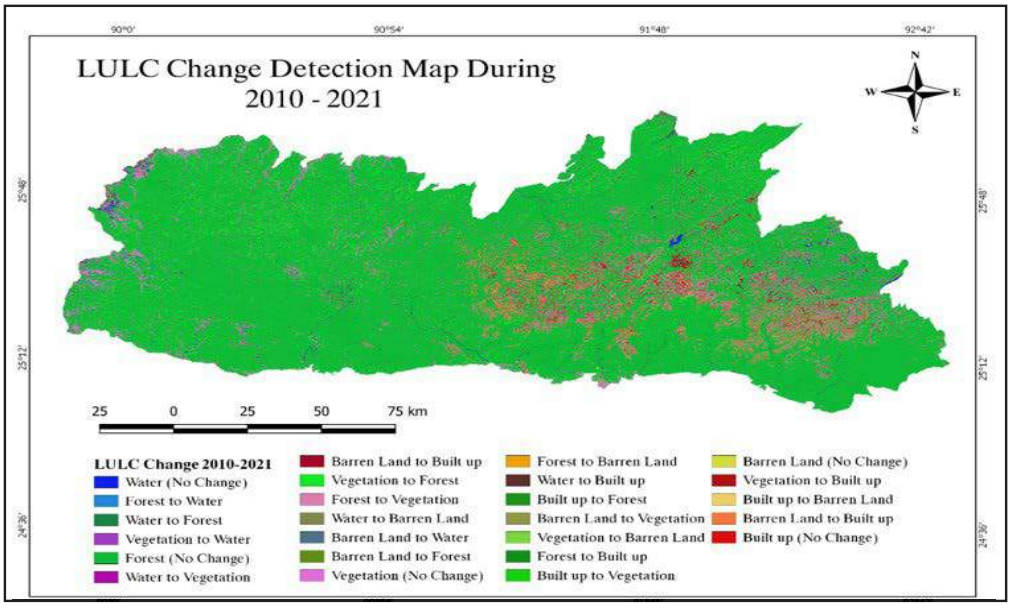


Fig. 3: Land use Land Cover Map of Meghalaya for the Years 2000, 2010, and 2021

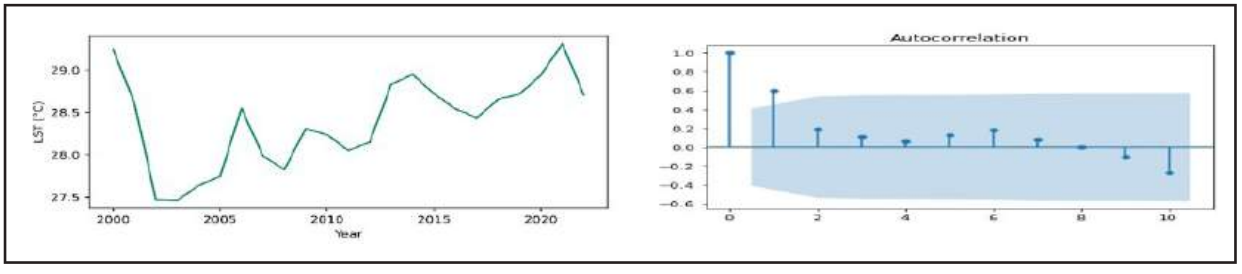


(A)



(B)

Fig. 4: The change detection map of Meghalaya is presented in two subgraphs (A) represents change detection map from 2000 to 2010 and (B) represents the change detection map from 2010 to 2021.



(A) (B)

Fig. 5: Represents two graphs; sub-graphs (A) represent the trend of LST of Meghalaya from 2000 to 2021, and (B) represent the Autocorrelation plot of LST.

The green color of Fig. 3 represents forest; the blue color represents water; the pink color represents vegetation; the yellow color represents barren land; and the red color represents buildup area. The total area cover in each class is presented in Table 2. To evaluate the authenticity of the results we also conducted accuracy measurements present in Table 3.

To evaluate the authenticity of the LULC map four evaluation measures has been utilized viz. user accuracy, producer accuracy, kappa and overall accuracy. Higher accuracy indicates the effectiveness of a classification algorithm in correctly identifying instances of a particular class among all the instances that truly belong to that class in reality.

Our next aim is to create a change detection map for 2000 to 2010 and 2010 to 2021. A change detection map indicates areas where changes have occurred between two or more periods (Fig. 4). These changes can include alterations in land cover, land use, infrastructure, vegetation cover, water bodies, and other features on the Earth's surface. Change detection maps are typically created by comparing remote sensing data, such as satellite imagery or aerial photographs, acquired at different time points. The process involves image classification to identify areas where significant changes have taken place. The outcome of this observation is to understand the maximum conversion of area, direction of conversion, and rate of the conversion. To justify the hypothesis, a change detection map is an important parameter. The maximum changes in land cover in the last 22 years presented in Fig.8 and Fig. 9 represent the percentage of area that converted to build-up area at the same period.

To understand the relationship between changing land cover and LST in the past 22 years we further conducted a trend analysis test on LST. The LST data pattern over the specified period is depicted in Fig. 5(A). We conducted a Mann-Kendall test to investigate the trend in LST. This non-parametric test is particularly useful when data is not normally distributed. It helps us understand whether there is a monotonic upward, downward, or no trend in the data. Additionally, an autocorrelation plot (Fig. 5(B)) was employed to detect correlations among data points in the LST dataset. This step is crucial for determining whether the basic Mann-Kendall test suffices or if a modified Mann-Kendall test is necessary for analysis. The statistics of the test are presented in Table 4.

Our next phase is to find out the factors affecting LST. Meanwhile, we performed the Person's correlation test

Table 4: Parameter statistics of Mann-Kendall test

Parameter	Value
h	True
p	<0.05
Tau	0.438
slope	0.061

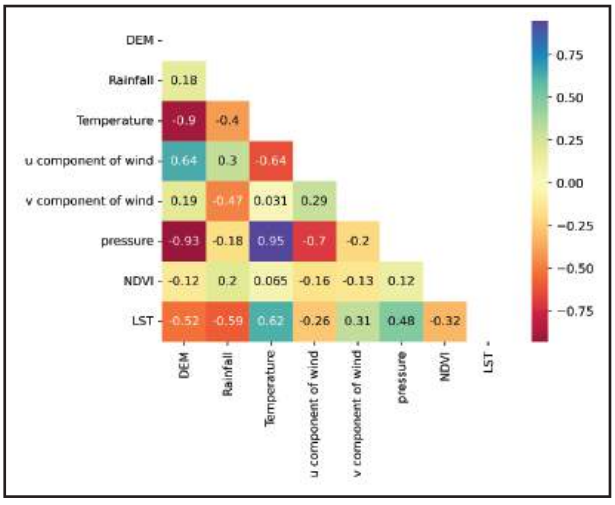
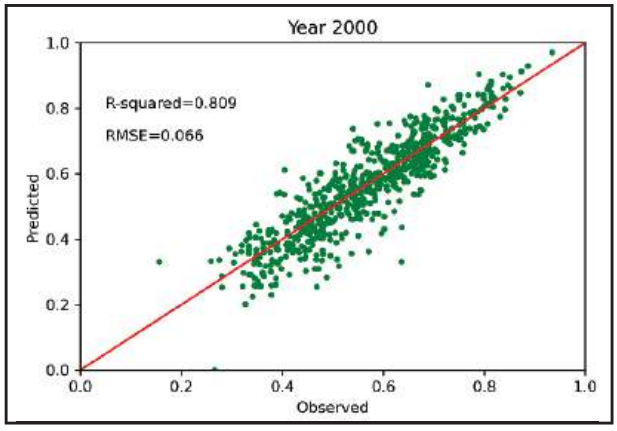


Fig. 6: Pearson's Correlation Map

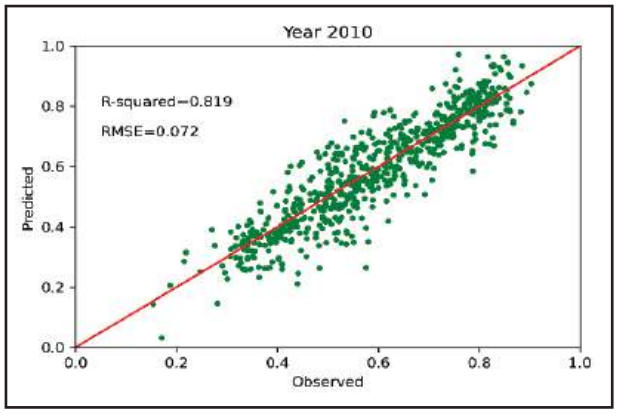
to understand the linear correlation between the factors. The value of this test ranges from -1 to +1. A value closer to -1 indicates a negative correlation, and a value closer to +1 indicates a positive correlation between the two features (Fig. 6). This method is used to understand linear relationships. However, most of our data are nonlinear, so we further conducted a regression analysis to understand the nonlinear relationship. Fig. 7 presented regression analysis, where the x-axis presented the actual value and the y-axis presented the observed value. The red line represents the best-fit line; data points closer to the best-fit line indicate the prediction of the model is accurate. Further, to measure the accuracy of the model, we calculated the r-square and RMSE values of the model.

DISCUSSION

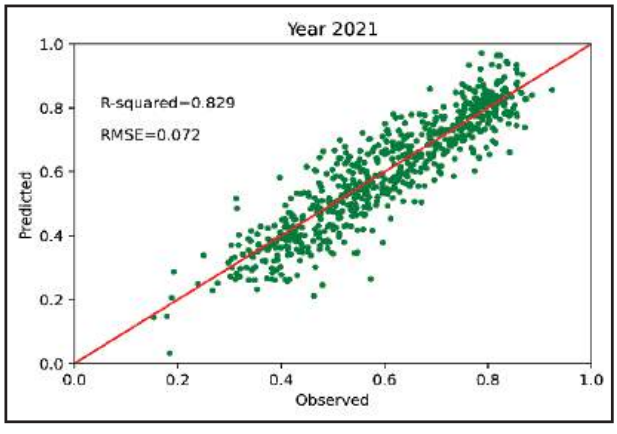
Processing voluminous satellite data can be incredibly challenging and time-consuming, necessitating platforms such as GEE for preprocessing and classification. We utilized random forest algorithm to generate an accurate land use land cover map of Meghalaya. Fig.3 depicts the classified map for 2000, 2010, and 2021, which illustrates each year's different land cover classes. The area calculation of the various land cover classes can be found in Table 2. These



(A)



(B)



(C)

Fig.7: Represents scattered graph, sub-graphs (A) represent observed vs. predicted graph for 2000, (B) represent observed vs. predicted graph for 2010, and (C) represent observed vs. predicted graph for 2021.

Between 2000 and 2010, Meghalaya experienced significant figures collectively indicate that the 22,400 km2 study area underwent significant changes. The overall water body decreased by 69.01% over the three years. 2000 water constituted 1.60% of the total area, but by 2021, it had been reduced to 0.50%. deforestation, with forest land being converted to vegetation land. This resulted in approximately 85.34% of the land being deforested in 2000, which decreased to 81.18% in 2010. The deforestation rate continued to decrease, and reforestation occurred between 2010 and 2021, resulting in an overall loss of 1.28% of forest land cover.

Furthermore, there was a 78% increase in vegetation land between 2000 and 2010, with an overall increase of 55.18% in vegetation land from 2000 to 2021. This suggests that some measures have been taken to reduce deforestation and promote vegetation growth.

Between 2000 and 2021, there was a notable reduction in barren land area, decreasing from 1197.84 km^2 to 56.80 km^2, marking a substantial decline. This reduction signifies a significant alteration in land cover, with approximately 95.25% of the barren land converted to different land cover types over the specified period.

Table 2 illustrates a remarkable surge in the buildup area, particularly notable from 2010 to 2021, experiencing an approximate growth rate of 223.54%. Cumulatively, there was an overall increment of 3,785.45% in the buildup area from 2000 to 2021. This rapid increase indicates a trend towards unplanned urbanization, which in turn poses threats to biodiversity conservation efforts.

To ascertain the accuracy and reliability of the classified map, four accuracy measures were employed: user's accuracy, producer's accuracy, kappa coefficient, and overall accuracy. All accuracy metrics surpassed the 81% threshold, indicating the robustness and efficacy of the classification methodology utilized in this study.

The findings underscore the significant changes in land cover patterns over the studied period and emphasize the urgency of implementing sustainable land management practices to mitigate the adverse impacts of rapid urbanization on biodiversity and ecosystem services.

LULC Change Detection

The change detection maps, presented in Figures 4(A) and 4(B), depict the overall transition in land cover patterns for the periods 2000 to 2010 and 2010 to 2021, respectively.

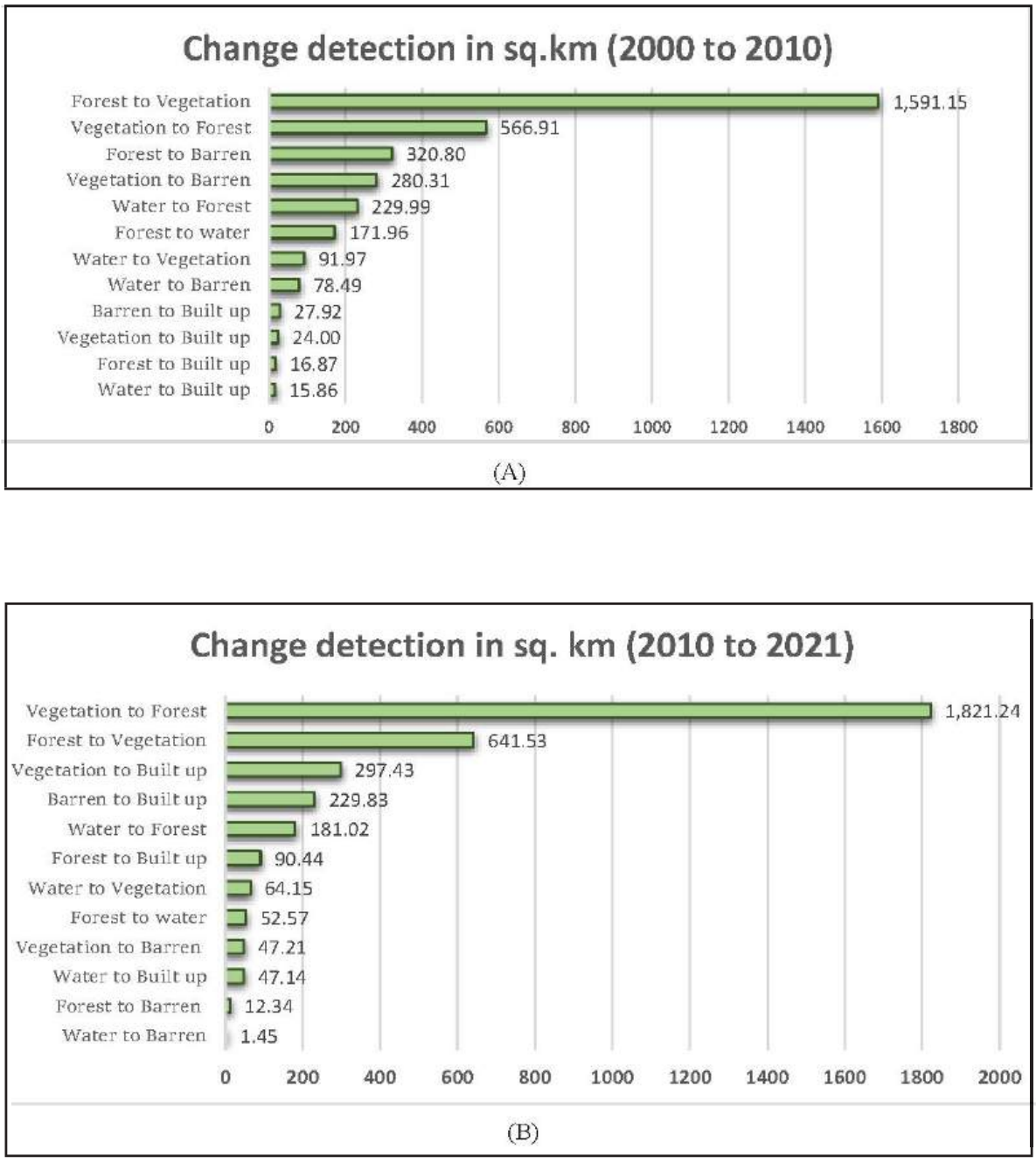


Fig. 8: Represents area (Km^2) conversion between classes with a bar graph; subgraphs (A) represent the change detection graph from 2000 to 2010, and (B) represent the change detection graph from 2010 to 2021

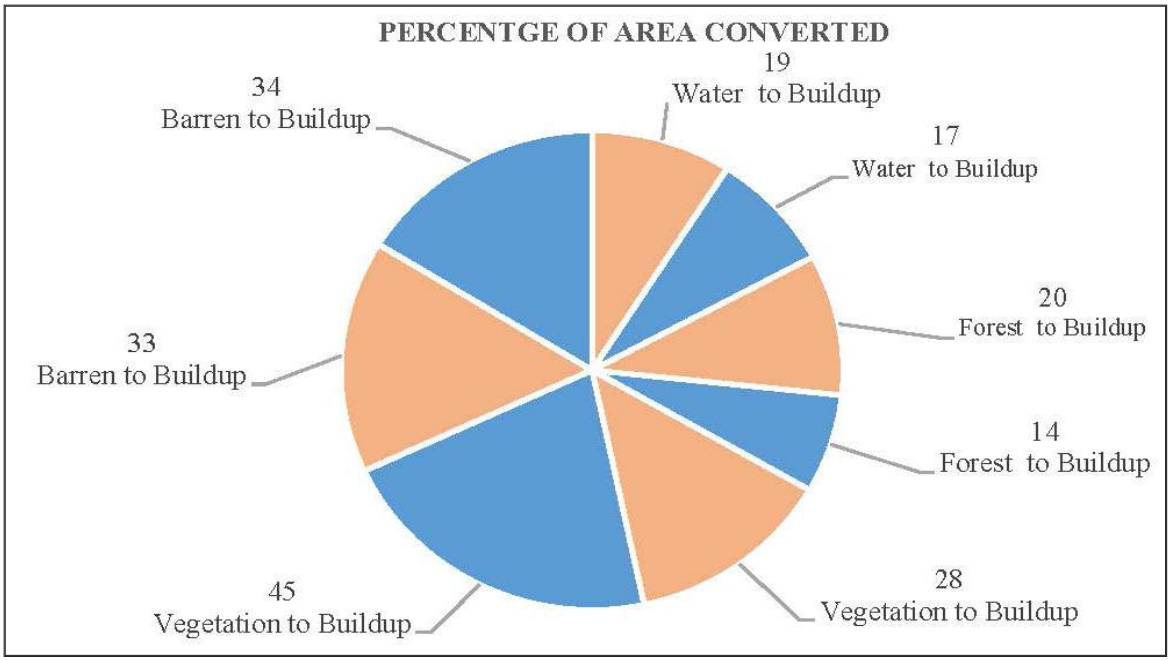


Fig. 9: Represents Percentage (%) of Area Vonversion from other Classes to Build-up

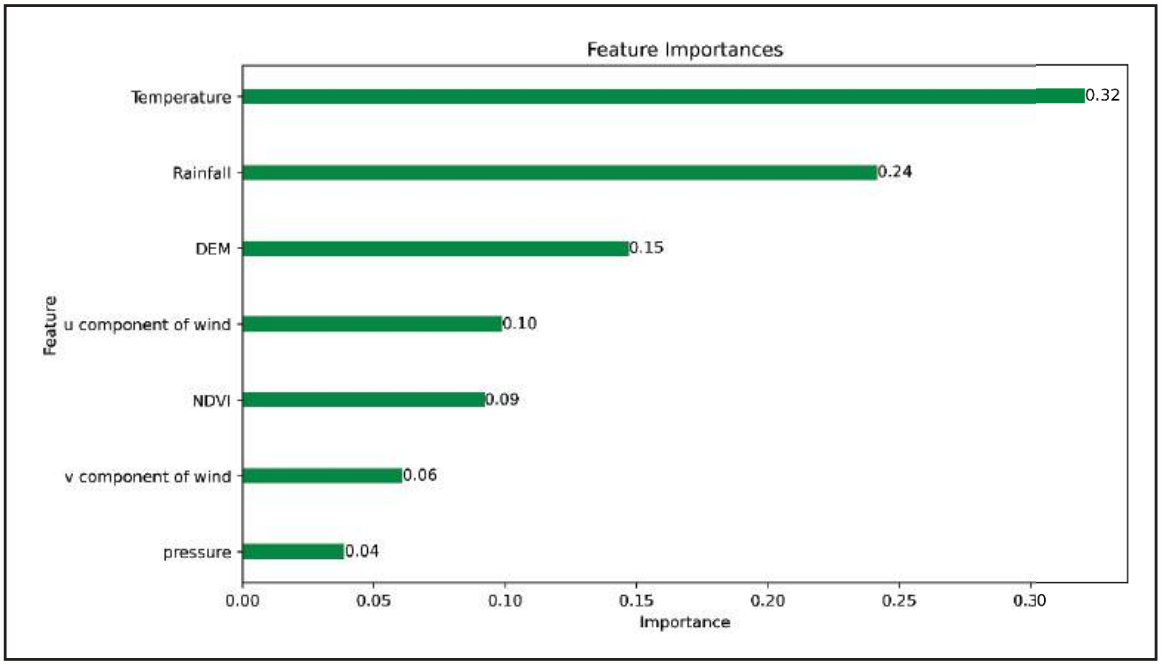


Fig.10: Feature Importance Graph

To discern significant changes, the data is further visualized through bar graphs in Figures 8(A) and 8(B).

Fig. 8(A) illustrates that from 2000 to 2010, a considerable area of approximately 1591.15 km^2 underwent a transition from forest to vegetation land, marking the most substantial change observed. Additionally, a notable conversion of approximately 566.91 km^2 from vegetation to forest land was noted. Other significant land cover changes include forest to barren land, vegetation to barren land, water to vegetation, and water to barren land. Minor changes were observed in the remaining land cover classes.

Conversely, in Fig. 8(B), covering the period from 2010 to 2021, notable transformations in land cover are depicted. The most prominent change observed was approximately 1821.34 km^2 between vegetation and forest areas. Conversely, approximately 641.52 km^2 of land transitioned from forest to vegetation. Additionally, approximately 297.43 km^2 of vegetation land was converted into build-up areas, while approximately 229.83 km^2 of barren land was transformed into build-up areas. Notable transitions observed in the 2010 to 2021 change detection plot include forest to build-up, water to vegetation, vegetation to barren, forest to barren, and water to barren land.

Further to analyze urbanization trends over the past two decades, we utilized pie chart (Figure 9). From 2000 to 2010, approximately 33% of barren land was converted to buildup areas, and from 2010 to 2021, this increased slightly to 34%, indicating improved land utilization. However, vegetation land conversion to buildup areas rose from 28% in the first decade to 45% in the second, raising concerns about food security and regional surface temperature. Additionally, 20% of forest land was converted to buildup areas in the first decade, with a slight decrease to 14% in the second. Despite the reduction, further decreases are necessary to protect forests, which are crucial for biodiversity and climate regulation.

LST Trend its Impacting Factors

This study aims to comprehend the LST trend and its correlation with urbanization and deforestation in Meghalaya. Initially, to ascertain the applicability of the Mann-Kendall test, we conducted an auto-correlation test. Fig. 5(A) and 5(B) illustrate the yearly LST and autocorrelation plots, respectively, with Fig. 5(B) indicating a slight correlation among data points. Subsequently, the Hamid and Rao Mann-Kendall test was employed, yielding a true h value and $p<0.05$, indicating a discernible trend. Tau and positive slope values further confirmed an increasing trend in LST data in the last 22 years. Notably, our study reveals that the recent rise in LST is directly linked to the augmented conversion of forest or vegetated land into built-up areas, aligning with findings published by (Alam *et al.*, 2022; Saha *et al.*, 2024).

The literature survey indicates that DEM, rainfall, temperature, and NDVI are correlated with LST. Additionally, we included pressure, the u-component of wind, and the v-component of wind in our analysis. The Pearson correlation graph (Fig. 6) illustrates that DEM, rainfall, NDVI, and the u-component of wind are negatively correlated with LST, while the remaining features show positive correlations. This finding aligns with previous studies (Feng *et al.*, 2019; Khandelwal *et al.*, 2018), which reported negative correlations between LST and DEM and NDVI. The negative relationship between LST and NDVI justified that the increasing LST trend is correlated with the deforestation or vegetation loss of a region. Further to examine the non-linear relationships, we conducted a Random Forest regression test. The scatter plot provides a visual representation, with R-square values ranging from 0.815 to 0.823, indicating that the models capture a significant portion of the data variability. Moreover, lower RMSE values suggest minimal prediction error. Additionally, the feature importance graph (Fig. 10) reveals that temperature, rainfall, DEM, and the u-component of wind, along with NDVI, are the most important variables in model building. However, the v-component of wind and pressure also significantly contribute to enhancing model performance.

Increasing LST and its Impact on our Food Security

The ramifications of elevated LST are profound, particularly impacting agriculture and ecosystems. Elevated temperatures induce heat stress in crops, leading to reduced photosynthesis, hindered growth, and decreased yields. Shifts in growing seasons disrupt planting and harvesting schedules, while intensified LST accelerates evapotranspiration rates, exacerbating water stress in plants and reducing water availability for crops. Furthermore, heightened temperatures expedite soil degradation processes such as erosion and desertification, compromising soil fertility and long-term crop health.

Changes in LST also disrupt ecosystems, altering habitats and affecting biodiversity. Urgent action is required to mitigate these impacts, including reducing greenhouse gas emissions, adopting improved agricultural practices,

and advocating for sustainable land management. Our research in Meghalaya reveals a concerning trend: LST has been steadily increasing at an annual rate of 0.05%, attributed to rapid unplanned urbanization, deforestation, and vegetation area depletion. However, potential remedies such as increasing NDVI through reforestation efforts and enhancing rainfall can effectively mitigate rising LST and its adverse effects.

These findings significantly impact stakeholders engaged in policymaking, urban planning, environmental conservation, and land management in Meghalaya. They underscore the necessity of implementing strategic interventions to counteract the detrimental effects of escalating LST. Measures such as restraining urban expansion, promoting sustainable land utilization practices, and facilitating vegetation restoration efforts emerge as pivotal strategies to mitigate adverse consequences on local ecosystems and agriculture.

Future studies should focus on long-term monitoring of surface temperature trends and their socio-economic impacts, providing deeper insights into environmental dynamics and aiding in formulating effective mitigation strategies.

CONCLUSION

This study presents a comprehensive analysis of the increasing LST trend in Meghalaya over the past 22 years, highlighting its correlation with unplanned urbanization, deforestation and changing climate patterns. Our observations from the LULC maps between 2000 and 2010 indicate a high rate of deforestation and a significant expansion of agricultural land. Furthermore, LULC change detection reveals substantial conversion of vegetation and barren land into built-up areas, alongside a notable shrinkage of vegetation and water bodies over the last two decades.

Correlation analyses revealed that DEM, rainfall, and NDVI are negatively correlated with LST, aligning with findings from other studies. Additionally, we incorporated wind components and pressure features into our study. To examine the nonlinear correlation of these variables with LST, we conducted a regression analysis. The results provided valuable insights, indicating that all variables are crucial for accurate LST prediction. Among these, temperature, rainfall, and DEM emerged as the most significant factors.

Overall, this study underscores the increasing LST trend as a consequence of unplanned urbanization and the reduction of forest and vegetation land in Meghalaya. These findings suggest the urgent need for more sustainable development plans for the future of the state. Our results could serve as a valuable asset for government authorities and policymakers to aid in creating better development strategies. While this study focused on data from the last two decades, incorporating more extensive datasets could further enhance analysis and decision-making processes.

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Handling Gender Bias in Neural Machine Translation: A Focus on English-Khasi Language Pair

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Abstract—Machine Translation systems have progressed tremendously over the years and have enhanced cross-lingual communication. Although machine translation has advanced from a rule-based to a neural machine translation method, a new issue occurring in most machine translation systems, such as gender bias, cannot be ignored. Gender bias not only affects translation accuracy but also has an impact on societal prejudices and often promotes inequalities and stereotypes. This study attempts to address the challenges of gender bias in neural machine translation for English-Khasi, a low-resource language pair, where data scarcity increases the risk of biased translations. To the best of our knowledge, this is the first attempt to report a study on gender bias in the neural machine translation task of English-Khasi language pair. We use two different methods; a data augmentation technique and a transfer learning method tailored to the linguistic and socio-cultural characteristics of the target language. To implement the two methods, we manually build a sizeable gender-balanced English-Khasi parallel corpora to handle gender bias in English-Khasi neural machine translation systems. Through empirical evaluation of low-resource language pairs, English-Khasi, we demonstrate the effectiveness of the transfer learning approach in reducing gender bias while maintaining translation quality.

Keywords: Gender bias information, Khasi, Data augmentation, Transfer learning, Neural machine translation.

INTRODUCTION

In an age of rapidly advancing technologies, machine translation has become essential in bridging linguistic gaps and enabling communication across cultural domains. Gender bias, a subtle yet significant issue persists beneath this technological progress, which is a serious concern about fairness and the inclusiveness of societal prejudices. Gender bias in machine translation refers to the tendency of translation algorithms to produce gender-related imbalances, which often occur due to the morphological inflection of nouns and pronouns while translating a source language to a target language. This issue is a growing concern that can affect the fairness of machine translation systems and therefore presents a significant challenge that needs to be addressed.

Neural machine translation (NMT) systems rely on word embedding (Espana-Bonet *et al.*, 2017; Sennrich and Haddow, 2016) in which a sentence is represented in the form of vectors of real numbers. These vectors can capture the semantic relationship between words in sentences, thus

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allowing an NMT system to translate each word efficiently. Word embedding is often trained on large corpora of text data. Training data can contain inherent biases in a society where certain occupations or roles can be predominantly associated with a specific gender. The system learns these biases from the training data, which can lead to a biased representation in the word embedding. The biased word embedding used by the NMT system can propagate the gender biases learned throughout translation. The system may learn to associate certain words with the specific genders based on biased word embedding, thus leading to biased translations.

NMT for gendered languages in which different words or forms are used based on the gender of the subject, can amplify gender bias in translations and reinforce stereotypes. This phenomenon usually occurs if one of the language pairs is a gendered language, such as English-Spanish (Escud´e Font and Costa-juss`a, 2019) or English-Khasi. Spanish and Khasi are both gendered languages, whereas English is not a gendered language. Thus, cases of gendered pronoun errors often occur in NMT tasks of such language pairs. An occurrence of gender disagreement in English-Khasi NMT (Hujon *et al.*, 2024) was recently reported in our previous work. One of the major causes of this error is the inadequate information required to aid in the correct translation of gendered pronouns in the parallel corpora. The results often exhibit gender stereotypes, which occur for various occupations, such as 'Doctor', is translated as a masculine pronoun, whereas 'Nurse' is often translated as a feminine pronoun. An example, 'Jane is a good doctor and she works in the village hospital' is often translated as 'Ka Jane ka dei *u* doktor ba bha bad *u* trei ha ka hospital shnong' with masculine *u* instead of the feminine *ka*.

Existing datasets like Winobias (Zhao *et al.*, 2018) and Winogender(Rudinger *et al.*, 2018) are available for a few high-resource languages for performing gender bias studies. Few works on NMT for English-Khasi language pair(Hujon *et al.*, 2024) (Singh and Hujon, 2020; Hujon *et al.*, 2023a) are reported, however, no report is found on gender bias. A dataset for the Khasi language that can aid in the English-Khasi NMT for addressing the issue of gender bias does not exist so far. This paper aims to delve into this issue and attempt to reduce gender bias in the machine translation of English to Khasi. An English-Khasi gender-balanced dataset is specifically created manually and experimented with using two different methods to handle gender bias. The NMT systems are evaluated using quantitative and qualitative metrics. The empirical results demonstrate that these methods can significantly reduce gender bias in the English-Khasi NMT.

The significant contributions of this paper are:

1. A sizeable parallel corpus is built for English-Khasi which is manually digitized and aligned.
2. A sizeable gender-balanced parallel corpus is built for English-Khasi which is manually translated and aligned.
3. The transfer learning method and data augmentation method are adapted and implemented for handling gender bias in the NMT systems of English-Khasi.
4. Quantitative and qualitative evaluation and analysis of the two methods are performed.

The paper's structure is as follows: Section 2 delves into the related work, while Section 3 outlines the research methods. Furthermore, Section 4 explains the experimental setup, Section 5 analyzes and discusses the experimental results of the various models, and finally, Section 6 presents the conclusion.

RELATED WORKS

Over the years, numerous works have contributed to the advancement of NMT. With the introduction of encoder-decoder architecture (Sutskever *et al.*, 2014), a crucial foundation was made for NMT. Based on this architecture, various works are reported for many language pairs across the globe. Subsequent research to improve translation accuracy and multiple aspects of NMT is performed and reported, such as the attention mechanism (Bahdanau *et al.*, 2016). Recently, transfer learning has emerged as a new approach for NMT (Zoph *et al.*, 2016), especially in dealing with issues of translation accuracy for low-resource languages. Another report using transfer learning has shown that transfer learning can also be applied to languages that are not linguistically related (Kocmi and Bojar, 2018).

Some existing works have attempted to mitigate gender bias in machine translations. One of the early works reported is a gender-enhanced NMT (Vanmassenhove *et al.*, 2018). The technique applied is by tagging the dataset in which gender information is injected into the dataset to reduce gender bias. The experiments mainly focused on language pairs that express grammatical gender. The results report significant improvements over state-of-the-art baseline systems. Word embedding is found to be another cause of gender bias in machine translations. The report shows that

word embedding can be severely biased, and a technique by debiasing the word embedding has been shown to reduce gender bias (Bolukbasi *et al.*, 2016a) significantly. Another work was reported using debiasing of word embeddings as a technique to handle gender bias in neural machine translations (Bolukbasi *et al.*, 2016b). Algorithms for debiasing and metrics to quantify direct and indirect gender biases in embeddings are implemented with significant improvement. The issue of gender bias also occurs in text emotion detection tasks. A report in line with this used a data augmentation method (Odbal *et al.*, 2022) where the gendered words are swapped using a bidirectional dictionary of gender pairs and a method of adversarial training, which showed a significant result in mitigating gender bias. Another report (Costa-juss`a *et al.*, 2022) explores gender bias in neural machine translation systems and investigates how different multilingual architectures can affect bias. For the study, two methods are proposed; one is based on word embedding, and the second is based on the attention mechanism. Gender information is encoded by using an SVM to classify occupations into three groups: male, female, and neutral. The systems are trained with the Europarl datasets for four languages: English, Spanish, French, and German. The results are analyzed based on BLEU and gender accuracy. The result shows that gender bias can occur in the source embedding, and algorithms of the implemented systems can also amplify the problem. A study on machine bias in terms of gender by Google Translate was performed and reported (Prates *et al.*, 2020). It reported a comprehensive study of twelve different languages. A set of sentences was prepared using the format 'He\She is an < *Job position* >', where < *job position* > is replaced by different job positions for both males and females. These sentences were created for twelve gendered neutral languages and translated to English using Google Translate. The report shows that Google Translate produces outputs that are predominantly male-dominated for most job positions. The study on the distribution of translated gender pronouns for each occupation category shows that 71.624% are male pronouns for Science, Technology, Engineering, and Mathematics occupations which are grouped under the STEM occupation category whereas only 4.219% are female pronouns and 11.181% are neutral pronouns. Another report on the study of a gender translation error in NMT systems (Wisniewski *et al.*, 2022) presented the results of the analyses of the flow of gender information between the Encoders and Decoders. A control test set consisting of 3394 gender-balanced parallel sentences for the French-English language pair is used. The sentences are created using the following template:

Type 1: (DET) (N) a termin´e son travail.

Type 2: The (N) has finished (PRO) work.

In the above template, (N) is the noun based on occupations, (DET) is the determiner for the French language, while (PRO) is the English possessive pronoun. The experiments and study are performed on the French-English parallel corpus from the WMT'15 'News' task (Bojar *et al.*, 2015). The method to mitigate gender bias through margin-augmented training loss has shown a significant result in improving the information flow between source and target in NMT systems.

Winobias (Zhao *et al.*, 2018) is a dataset designed to explore gender bias in terms of coreference resolution. The dataset consists of 3160 sentences covering around 40 stereotype occupations created in Winograd-style (Rahman and Ng, 2012) in two forms as given in the templates given below:

Type 1 : (entity1) (interacts with) (entity2) (conjunction)(pronoun) (circumstances)

Type 2: (entity1) (interacts with) (entity2) and then (interacts with) (pronoun) for (circumstances)

Winogender (Rudinger *et al.*, 2018) is another dataset which is also designed to resolve coreferences in gender bias. It is similar to Winobias but additionally includes gender-neutral pronouns.

One of the existing works on the English-Khasi language pairs (Hujon *et al.*, 2024) reported on neural machine translation systems using Long-Short-Term-Memory (LSTM), Gated Recurrent Unit (GRU), and transformer. The evaluation is performed on two different test data, within the domain and out of the domain. The study is performed on the English-Khasi dataset, which consists of 41529 parallel sentences. Considering the close linguistic relationship between languages of the same classification, Vietnamese, which belongs to the same group of Austroasiatic languages as the Khasi language, is chosen for the study to improve the translation accuracy. The NMT system achieved a superior performance in comparison to all the other models in the quantitative and qualitative evaluation results. The report also discusses its findings on gender disagreement observed in the outputs of the various NMT systems implemented. Transfer learning methods have shown promising results for low-resource languages (Zoph *et al.*, 2016; Nguyen and Chiang, 2017; Kocmi and Bojar, 2018), and reports show that when the parent models are trained on a high resource language pair and the child model are trained on the low

resource language pair, appears to have a positive impact on the performance of the child model. Another NMT system is also reported using an English-French language pair on the parent model and an English-Khasi language pair on the child model (Hujon *et al.*, 2023b) with significant results.

METHOD

Recurrent neural networks (RNN) have been successful in many neural machine translation tasks for various language pairs. However, recently with the introduction of the transformer (Vaswani *et al.*, 2017), NMT systems have achieved more accurate translations. The central core of the state-of-the-art transformer architecture is the self-attention mechanism and the positional encoding.

$$PE_{(pos2i+1)} = \cos\left(\frac{pos}{10000^{\frac{2i}{d_{model}}}}\right) \quad (1)$$

$$PE_{(pos2i)} = \sin\left(\frac{pos}{10000^{\frac{2i}{d_{model}}}}\right) \quad (2)$$

This mechanism allows the model to capture long-range dependencies and focus on essential words in a sentence to generate the translated output. The positional encoding is performed by using a *cos* function as in Equation 1 and *sin* function as in Equation 2 on the odd index and even index of the input vector, respectively.

$$Multi\text{–}Head\ (output) = Concant\ (z_0, z_2, z_3, z_4, z_5, z_6, z_7) = x, d_{model} \quad (3)$$

$$Attention\ (Q, K, V) = softmax\left(\frac{QK^T}{\sqrt{d}K}\right)V \quad (4)$$

A multi-head attention is performed before going through self-attention and this is accomplished by Equations 3 and 4. In Equation 3, z_i is the output of the multi-head attention, d_{model} is the input dimension and x is a sequence of words, and in Equation 4, the terms Q, K and V are the query, key which is the vector representation of the words in a sequence, and value respectively. The transformer has achieved state-of-the-art performance on various NMT tasks with improved translation quality. For this reason, we have implemented our models using the transformer architecture (Vaswani *et al.*, 2017).

[1]https://storage.googleapis.com/gresearch/translate-gender-challenge-sets/data/Translated/Wikipedia/Biographies/-/EN_ES.csv

One of the significant causes of gender bias is the imbalances of data in the parallel corpora for all genders. Since most of the data collected are from existing sources originally documented by humans, the presence of biases in the text is typical. Usually, most documents are influenced by societal prejudices. Various occupations are associated only with a specific gender. A few examples of occurrence of such association for occupations and genders are:

Doctor	Male
Nurse	Female
Babysitter	Female
Captain	Male
Police Officer	Male
Professor	Male
Receptionist	Female
Pilot	Male
Surveyor	Male

This problem manifests itself in the NMT systems of English to Khasi, which leads to gender bias in the output of the systems.

TECHNIQUE FOR REDUCING GENDER BIAS

To handle gender bias in the neural machine translation of English to Khasi, we prepare a gender-balanced dataset Dataset GB. This dataset is manually created to handle the issue of imbalances of gender information in the English-Khasi parallel corpora. The Translated Wikipedia Biographies are professionally translated and are available in two pairs of languages, English-Spanish and English-German. The sentences in the dataset represent an entity identified in the biographies as feminine or masculine, a band, or a team. Each dataset instance consists of 8 to 15 sentences referring to the central entity. Our gender-balanced dataset consists of two sets of data; 1363 English sentences are extracted from the existing Translated Wikipedia Biographies and are then manually translated from English to Khasi. The second set consists of 586 pairs of gender-balanced sentences, which are manually created for both English and Khasi. The sentences are short and include various occupations and gender entities to complement the main dataset in terms of gender information. These sentences are generally of two forms:

Form1: (entity1) (verbal phrase) (pronoun) (circumstances)
Form2: (entity1) (verbal phrase) with (pronoun)(entity2) (circumstances)

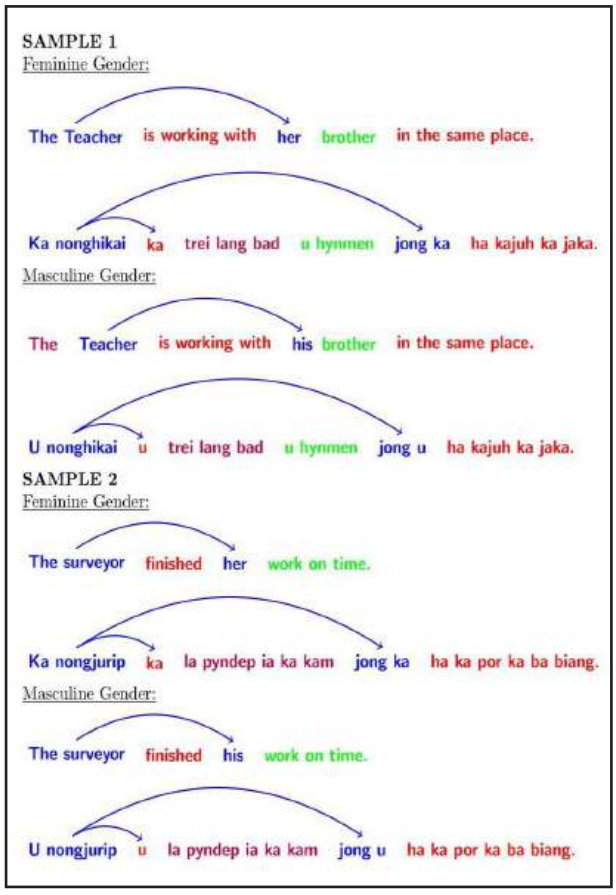


Fig. 1: Gender balanced sentences for English and Khasi pair

For each occupation, we prepare two sets of sentences in English language and Khasi language, associated with masculine and feminine gender as in Figure 1. Each sentence in Figure 1 consists of an entity and a gendered pronoun associated with it, indicated by the direction of the arrow.

We built three datasets as in Table 1; $Dataset_{EK}$ is the main dataset of 50691 parallel sentences. $Dataset_{EK}$ is built using online data from the Bible (Life.Church/YouVersion, 2021a; Life.Church/YouVersion, 2021b) and existing books (Hujon and Singh, 2018) in Khasi language that are translated from an English source. The English-Khasi parallel corpora are manually digitized and aligned. $Dataset_{GB}$ is the gender-balanced dataset, and $Dataset_{CD}$ is the augmented dataset consisting of text from $Dataset_{EK}$ and $Dataset_{GB}$. The $Dataset_{EK}$ dataset, the $Dataset_{GB}$ dataset, and the $Dataset_{CD}$ consists of *9,28,495* words, *34,348*, and *9,62,843* words in total in the English corpus, whereas the $Dataset_{EK}$ dataset, the $Dataset_{GB}$ dataset, and the $Dataset_{CD}$ consists of *12,31,938* words, *49,584*, and *12,81,522* words in total in the Khasi corpus and are distributed for train, validation and test data as shown in Table 1.

We initially implemented the baseline model $NMT_{baseline}$ using a transformer that is trained on the English-Khasi parallel corpora. The baseline model is trained on the main dataset $Dataset_{EK}$. We attempt to reduce gender bias by using two different methods.

In the first method as shown in the schematic diagram in Figure 2, we take the English-Khasi parallel corpora and the gender-balanced parallel corpora and perform data augmentation. In the process, we make sure that data of the gender-balanced dataset is distributed proportionately as train, validation, and test data. Next, the augmented English-Khasi dataset $Dataset_{CD}$, goes through a word segmentation process. We apply two different word segmentation methods, that is, word segmentation method by tokenization using Mosesdecoder toolkit (Koehn *et al.*, 2007) and word segmentation method by subword byte pair encoding (Sennrich *et al.*, 2016) technique. The tokenized augmented English-Khasi dataset and the subword BPE augmented English-Khasi Dataset are trained on different NMT systems.

In the second method as shown in the schematic diagram in Figure 3, the English-Khasi parallel corpora and the gender-balanced parallel corpora initially go through a word segmentation process. Similar to the previous method, we apply two different word segmentation methods, that is, word segmentation method by tokenization using Mosesdecoder toolkit (Koehn *et al.*, 2007) and word segmentation method by subword byte pair encoding(Sennrich *et al.*, 2016) technique, and these give rise to two different pair of datasets; the tokenized English-Khasi dataset and tokenized

Table 1: Datasets Statistics

Dataset	Number of sentences			English(in number of words)			Khasi(in number of words)		
	Train	Validation	Test	Train	Validation	Test	Train	Validation	Test
$Dataset_{EK}$	46263	1772	2656	864465	27356	36674	1145840	36684	49414
$Dataset_{CD}$	47838	2026	2776	892553	31251	39039	1186444	42343	52735
$Dataset_{GB}$	1575	254	120	28088	3895	2365	40604	5659	3321

English-Khasi gender balanced dataset, the subword BPE English-Khasi dataset, and subword BPE English-Khasi gender balanced dataset. Using the two tokenized datasets, we create a joint tokenized vocabulary, and similarly, using the two subword BPE datasets, we create a joint subword BPE vocabulary. Next, we implement two different NMT systems using the transfer learning approach.

Both the parent model and the child model share a joint vocabulary. For the first NMT system using the transfer learning approach, we train the parent model using the transformer architecture on the tokenized $Dataset_{EK}$ dataset till convergence, and the weights of the parent model are used to initialize the child model. The child model is trained on the tokenized English-Khasi gender-balanced dataset, $Dataset_{GB}$, and shares the joint tokenized vocabulary with the parent model. For the second NMT system using the transfer learning approach, we train the parent model and also use the transformer architecture on the subword BPE $Dataset_{EK}$ dataset till it converged, and the weights of the parent model are used to initialize the child model. Next, the child model is trained on the subword BPE English-Khasi gender-balanced $Dataset_{GB}$ dataset. The child model shares the joint subword BPE vocabulary with the parent model.

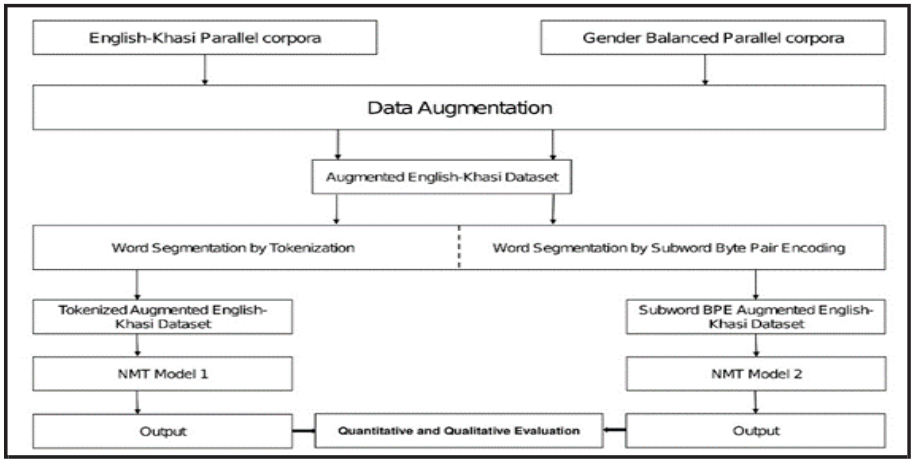


Fig. 2: Schematic Diagram for the Data Augmentation Method

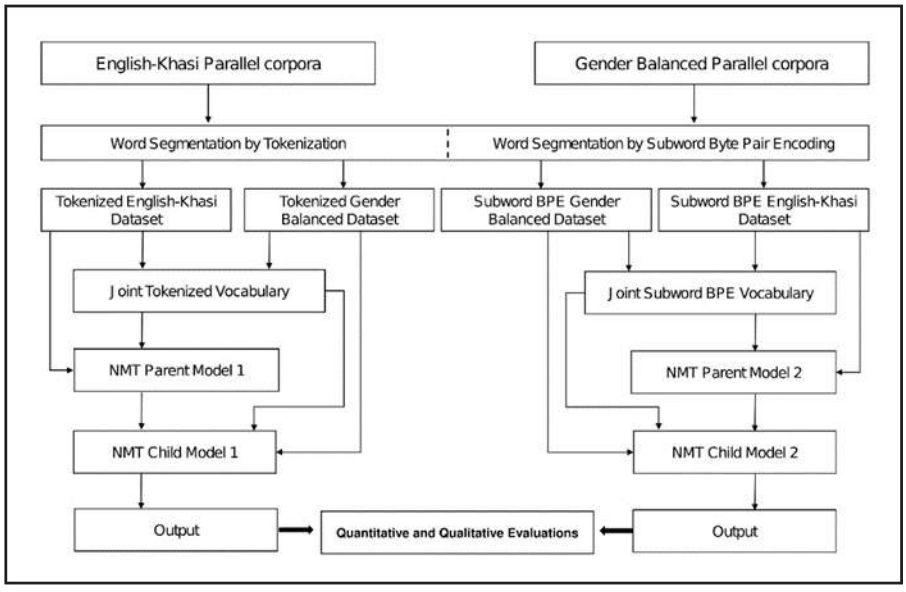


Fig. 3: Schematic Diagram for the Transfer Learning Method

Evaluation Method

Some commonly used evaluation methods are reported for NMT models of low resource languages (Chatzikoumi, 2020; Ranathunga *et al.*, 2023). Evaluation of the output of each model is performed using the sacreBleu (Post, 2018; Papineni *et al.*, 2002) script for automatic evaluation. We also performed a statistical evaluation (Koehn, 2009) based on *Precision*, *Recall*, and *F*1–*Measure* on a scale of 1 to 100. With regards to qualitative evaluation, two annotators evaluate the output on a scale of 1-5 based on *adequacy*- number of correct translated words, *fluency* - grammatical correctness based on word order agreement of the target language, and *gender accuracy* - number of correct translated pronoun in co-reference to a noun in the sentence. We also use the Spearman correlation coefficient as in Equation 5 for determining the inter-annotator agreement. An analysis of the correlation between the quantitative evaluation and qualitative evaluation is performed using the Pearson correlation coefficient as in Equation 6.

$$\rho = 1 - \frac{6\sum d_i^2}{n(n^2-1)} \tag{5}$$

$$r = \frac{n\sum xy - \sum x \sum y}{\left(\sqrt{(n\sum x^2 - (\sum x)^2}\left(n\sum y^2 - (\sum y)^2\right)\right)} \tag{6}$$

EXPERIMENTAL SETUP

The two datasets $Dataset_{CD,}$ *and* $Dataset_{GB}$ which are processed using two different word segmentation methods are used to train separate NMT systems to implement the two approaches. We implement two NMT systems which are trained using the data augmented datasets. The system NMT_{CD1} is trained on the $Dataset_{CD}$ tokenized dataset, and NMT_{CD2} is trained on the $Dataset_{CD}$ subword BPE processed dataset. Another two NMT systems using the transfer learning method are trained on the tokenized datasets and the subword BPE datasets. The parent model of the NMT_{TL1} system is trained on the $Dataset_{EK}$ tokenized dataset, and the child model is trained on the $Dataset_{GB}$ tokenized dataset. Similarly, the parent model of the NMT_{TL2} system is trained on the $Dataset_{EK}$ subword BPE dataset and the child model is trained on the $Dataset_{GB}$ subword BPE dataset.

The NMT systems are implemented using the transformer architecture (Vaswani *et al.*, 2017) with six layers and eight heads. We train the models using similar parameters: Adam optimizer, a learning rate of 2.0, a dropout rate of 0.2, and an attention dropout of 0.1.

The translation accuracy of the systems is evaluated on two test sets- $Testset_{CD}$ which is the test set of the augmented dataset and $Testset_{GB}$ which is the test set of the gender-balanced dataset. The quantitative evaluation uses BLEU, ChrF2, and TER. The qualitative evaluation is performed by human judgment based on *accuracy* and *fluency*. For qualitative evaluation, a Python script is used to randomly select 100 samples of sentences for each system. To evaluate the effectiveness of the systems in reducing gender bias, we evaluate the systems on another test set of 100 samples taken from the test set $Testset_{GB}$. The qualitative evaluations are performed by two annotators using two metrics- *adequacy* and *fluency* and *gender accuracy* by two annotators. To assess the inter-annotator agreement, we use Spearman correlation for both *adequacy*, *fluency*, and *gender accuracy*. Using Pearson correlation, we also correlate the BLEU scores with *adequacy* and *fluency*.

RESULTS AND ANALYSIS

The automatic scores are shown in Table 2 for the two test sets, $Testset_{CD}$ and $Testset_{GB}$. NMT_{CD2} achieved the highest score of 54.7 BLEU, 69.6 ChrF2 and Translation Error Rate of around 31 with $Testset_{CD}$, NMT_{CD2} also performed equally well with a slight difference of -0.1 BLEU compared to NMT_{CD2} while NMT_{TL2} achieved the highest score of 12.0 BLEU with $Testset_{GB}$. Compared to the baseline model, NMT_{CD2} shows an improvement of +0.7 BLEU and +0.4 ChrF2, whereas NMT_{TL2} achieved a slightly lower score for $Testset_{CD}$ but shows a significant improvement of +6.8 compared to the baseline model for $Testset_{GB}$. NMT_{CD1} and NMT_{CD2} also performed equally well with score of 10.8 BLEU and 11.3 BLEU on the gender-balanced test set. We observed that the models that are trained on the subword BPE datasets outperformed the other models; NMT_{CD2} with $Testset_{CD}$ and NMT_{TL2} with $Testset_{GB}$. The word embedding of the subword BPE data appears to have a positive impact on the quality of the output translated by the NMT systems.

Table 2: Automatic Scores

Model	$Testset_{CD}$			$Testset_{GB}$		
	BLEU	**ChrF2**	**TER**	**BLEU**	**ChrF2**	**TER**
$NMT_{Baseline}$	54.0	69.2	31.9	5.2	24.8	85.5
NMT_{CD1}	54.6	69.6	31.4	10.8	31.8	80.7
NMT_{CD2}	**54.7**	69.6	31.7	11.3	31.2	82.7
NMT_{TL1}	22.4	41.6	58.6	9.6	25.3	71.2
NMT_{TL2}	21.8	42.0	58.8	**12.0**	30.5	90.3

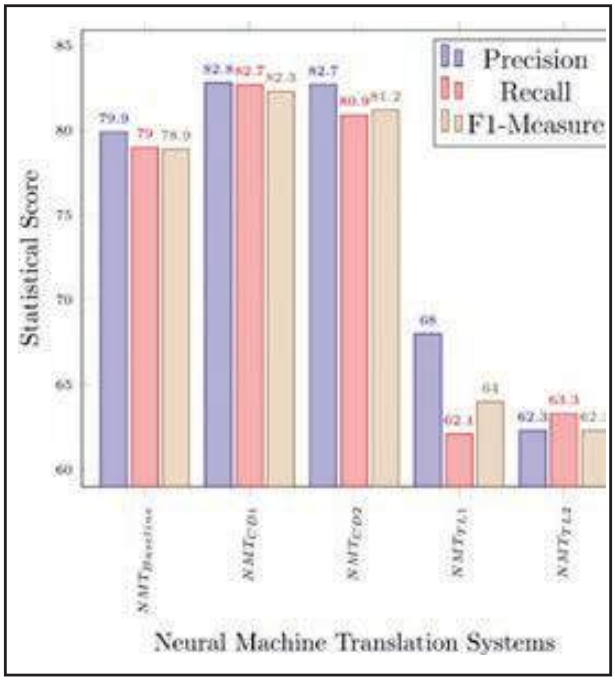
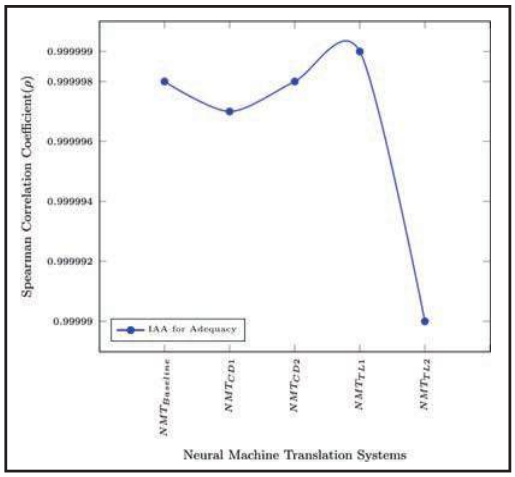


Fig. 4: Statistical Evaluations

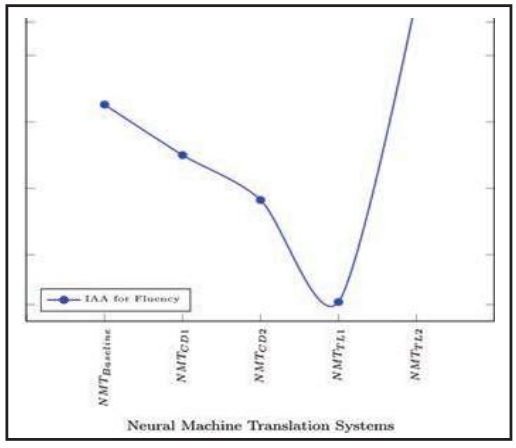
The statistical evaluation is performed, and the results are shown in Figure 4. We observed that the data augmentation models outperformed the other models in the experiment. NMT_{CD1} scored the highest with 82.3 F1-measure score, while NMT_{CD2} scored 81.2 F1-measure score. Both the data augmentation models, NMT_{CD1} and NMT_{CD2} outperformed the baseline model $NMT_{Baseline}$ by an improvement of +3.4 and 2.3 F1-measure score, respectively. The transfer learning models show a lower performance compared to the other models, but both models, NMT_{TL1} and NMT_{TL2} achieved good scores of > 60 F1-measure. On analyzing the automatic score in Table 2 and the statistical score in Figure 4, we find that the automatic scores of $Testset_{CD}$ correlate with the statistical scores, in which the data augmentation models achieved the highest scores in the quantitative evaluations. Considering Figure 4 and Table 3, we also observed a similar pattern in the results of the evaluations, where the proposed data augmentation models showed a higher performance than the other models and outperformed the baseline model.

Table 3: Human Evaluated Scores

NMT System	Adequacy Score	Fluency Score
$NMT_{Baseline}$	3.95	4.48
NMT_{CD1}	4.10	4.55
NMT_{CD2}	4.04	4.52
NMT_{TL1}	3.10	3.47
NMT_{TL2}	3.18	3.97



(a) IAA for Adequacy



(b) IAA for Fluency

Fig. 5: Inter Annotator Agreement (IAA)

The results of human evaluations as performed by the annotators are shown in Table 3. The Spearman correlation is implemented as in Equation 5. The Spearman correlation coefficients for the various NMT systems show a favourable inter-annotator agreement with overall scores of +0.9 for both *adequacy* and *fluency* as shown in Figure 5a and Figure 5b. Comparing the Spearman correlation coefficient between *adequacy* and *fluency*, we observed that human judgment by the annotators on *adequacy* is more correlated to one another than on *fluency*, as the task of evaluating the number of correct translated words can be performed using the same method, while the task of evaluating *fluency* is more difficult and human judgment can slightly differ while ranking each sample. The two data augmentation models NMT_{CD1} and NMT_{CD2} have outperformed the baseline model $NMT_{Baseline}$ in both *adequacy* and *fluency*. Even though NMT_{TL1} and NMT_{TL2} achieved slightly lower scores in human

evaluations among the models, the two models achieved significantly high scores of > 3 in *adequacy* and *fluency*.

We compared the automatic scores and human-evaluated scores using Pearson correlation as in Equation 6. The Pearson correlation coefficient for the various NMT systems is shown in Table 4. All the models show positive scores close to +1, which depicts a favourable correlation between automatic and human evaluation.

Table 4: Pearson Correlations between automatic and human evaluated scores

Model	BLEU Score and Adequacy(r_1)	BLEU Score and Fluency(r_2)
$NMT_{Baseline}$	0.408386899	0.456298011
NMT_{CD1}	0.687616319	0.344257435
NMT_{CD2}	0.653555117	0.407419022
NMT_{TL1}	0.408699657	0.225584008
NMT_{TL2}	0.585296315	0.408386899

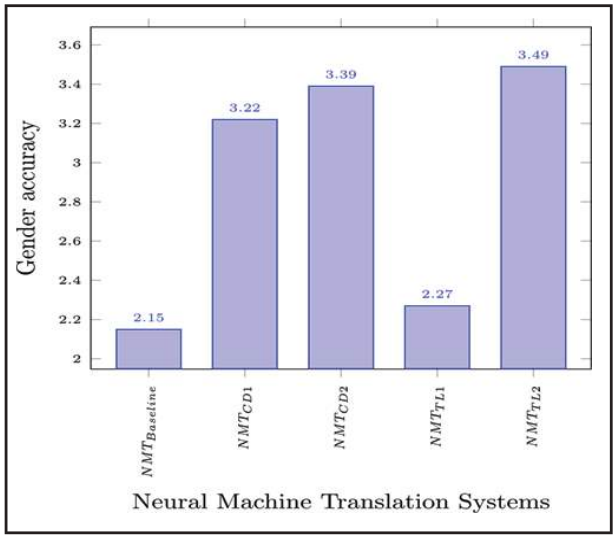


Fig. 6 : Gender Accuracy Scores of the NMT Systems

Gender accuracy is evaluated based on how many pronouns are translated correctly in coreference to each gendered entity in a sentence. Two annotators scored each sample on a scale of 1-5 with 5 as the highest. The scores are as shown in Figure 6. Just as in *adequacy* and *fluency*, the Spearman correlation of gender accuracy as shown in Figure 7 also illustrates a strong inter-annotator agreement with overall scores of +0.9 for *gender accuracy*. NMT_{TL2} achieved the highest score with 3.46875 and outperformed the baseline model by +1.32, closely followed by NMT_{CD1} and NMT_{CD2} which also outperformed the baseline models with an improvement of +1.069 and +1.23 respectively. Referring to Table 2 and Figure 6, we observed that the scores in *gender accuracy* correlate with the BLEU scores achieved by the models for $Testset_{GB}$ in which NMT_{TL2} model outperformed the other models. We also observed that the transfer learning systems NMT_{TL1} and NMT_{TL2} shows a slightly lower performance in translation accuracy as seen in automatic scores in Table 2, statistical scores in Figure 4, and human judgment score on *adequacy* and *fluency* in Table 3 but it shows a good improvement in terms of gender accuracy as seen in Figure 6. NMT_{TL1} outperformed the baseline system, while NMT_{TL2} achieved the highest performance compared to all the NMT systems.

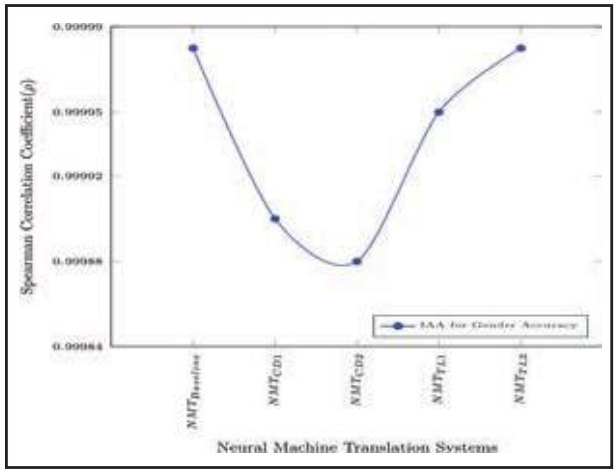


Fig. 7 : Inter Annotator Agreement (IAA) for Gender Accuracy

Output Analysis

We present a study on randomly selected sentences of the NMT systems experimented based on translation accuracy and gender accuracy concerning inputs and the corresponding reference texts.

Table 5: Sample Output-I: Short Sentence

Input	he will defeat kings all over the earth.
Reference	un jop ïa ki syiem baroh jong ka pyrthei.
$NMT_{Baseline}$	un jop ïa ki syiem ha kylleng ka pyrthei
NMT_{CD1}	un jop ïa ki syiem ha kylleng ka pyrthei.
NMT_{CD2}	un jop ïa ki syiem ha kylleng ka pyrthei.
NMT_{TL1}	un jop ia ki syiem jong ka pyrthei baroh kawei.
NMT_{TL2}	un jop ia ki syiem baroh ha ka pyrthei.

Table 6: Sample Output-II: Long Sentence

Input	What then? The people of Israel did not find what they were looking for. It was only the small group that God chose who found it; the rest grew deaf to God's call .
Reference	Kaei pat te ngin ïa-ong? Ki paid Israel kim shym la shem ïa kaei kaba ki ïawad. Ka la long tang ka kynhun kaba rit kaba U Blei u la jied, kaba la shem ïa kata; kiba sah na kita ki la set kyllut ïa ka jingkhot jong U Blei.
$NMT_{Baseline}$	Te uei ? Ki paid Israel kim shym shem aïu ki ïawad . Ka dei tang ka kynhun kaba rit kaba U Blei u la jied ïa ka ; kiba sah ki la nang san sha ka jingkhot U Blei.
NMT_{CD1}	Te? Ki paid Israel kim shym shem ïa kaei kaba ki wad. Ka long tang ka kynhun kaba rit kaba U Blei u la jied ïa ka; kaba sah ka la nang san sha ka jingkhot U Blei.
NMT_{CD2}	Kaei te ? Ki paid Israel kim shym shemïa kaei kaba ki wad . Ka dei tang ka kynhun kaba rit kaba U Blei u la jied ïa ka ; kaba sah ki la nang kyllut ban khot ïa U Blei.
NMT_{TL1}	Nangta pat ? Ki paid Israel kim shym shem ia kata ba ki lah khmih lynti ba ki ioh . Ka long tang ka kynhun kaba rit ba lah jied ban shem ia ka
NMT_{TL2}	Nangta ki paid Israel kim shym shem kat kaba ki dang wad . Ka dei tang ka kynhun kaba rit ba U kpa jong ki uba la lap ia ka ; kiwei pat ki la san ha ka jingkhot jong U pyrthei.

Considering translation accuracy, two samples of the outputs of the NMT systems are shown in Table 5 and Table 6 for short sentences and long sentences respectively. In Table 5, the input text 'he will defeat kings all over the earth' with the corresponding reference text 'un jop ïa ki syiem baroh jong ka pyrthei' is translated more or less accurately by all the NMT systems.

Table 7: Sample Output-III: Gender Accuracy

Input	*She* is *the new jailer* appointed recently
Reference	*ka* dei *ka nongap byndi ba thymmai* ba dang shu sl thung shen
$NMT_{Baseline}$	*Ka* dei *u nongpeit phatok uba thymmai*
NMT_{CD1}	*Ka* dei *ka nongpeit phatok kaba thymmai* ba la thu
NMT_{CD2}	*Ka* dei *ka nongap ing byndi*
NMT_{TL1}	*Ka* dei *ka nongap ing byndi ba thymmai*
NMT_{TL2}	*Ka* dei *ka nongap ing byndi thymmai* ba la thung

Each of the NMT systems maintains the Subject-Verb-Object word order agreement of the target language in their respective outputs and therefore achieves the fluency of the target language. Although the input phrase 'all over' is translated to 'ha kylleng' by $NMT_{Baseline}$, NMT_{CD1}, NMT_{CD2} instead of 'baroh kylleng', the output sentences of these systems convey a similar meaning with fluency. In Table 6, the phrase 'The people of Israel did not find what they were looking for' is translated more correctly to 'Ki paid Israel kim shym shem ia kaei kaba ki wad' by the data augmentation NMT systems and the baseline system. The outputs of the transfer learning NMT systems also efficiently translate the input sentence as in the reference text, with a few disagreements with the word order of the target language. Both the data augmentation NMT systems and the transfer learning NMT systems can translate most of the words as in the reference text. We also observed that the predicted outputs of the NMT systems correlate with the performance of the NMT systems in the quantitative evaluations and qualitative evaluations as in Table 2, Figure 4, and Table 3.

Considering gender accuracy, we also present a study on two randomly selected sentences as we have done for the analysis of translation accuracy. In Table 7, we observe that the occupation 'jailer' refers to a feminine gender in the input sentence, and the correct translation in the reference is 'ka nongpeit byndi', the word 'byndi' or 'patok' in the Khasi language can be used interchangeably. So 'ka nongpeit patok' is also a correct translation. We observed that the baseline model $NMT_{Baseline}$ translates into a masculine form 'u nongpeit patok'. The proposed models show a correct translation and also translate the correct gender pronoun of 'She' to 'ka'. Similarly, in Table 8, we observed that the occupation 'doctor' refer to a feminine gender in the input sentence and the translation to Khasi is 'ka doktor' as shown in the reference text. The baseline model $NMT_{Baseline}$, the NMT_{CD1} model and the NMT_{CD2} model translate to a masculine form 'u doktor', whereas the NMT_{TL1} model and the NMT_{TL2} model, both translate to the correct gender form. The translation in Khasi of the word 'sister' can be either 'ka para', 'ka para kynthei', 'ka hynmen' or 'ka hynmen kynthei', and we notice that all the models generate the correct translation in Khasi. Furthermore, the NMT_{TL1} model generates an almost exact translation as the reference text.

Table 8: Sample Output-III: Gender Accuracy

Input	My sister is working as a doctor in our local hospital and she is very good with kids
Reference	*Ka hynmen kynthei* jong nga ka trei kum *ka doktor* ha ka hospital shnong bad *ka* ba iadei bha bad ki khynnah rit
$NMT_{Baseline}$	*Ka para* jong nga ka trei kum *u doktor* uba stad tamïa kaei kaba *ka* la jia ha shnong rit ka bym salia eiei ruh shaphang ka jingïadei hapdeng jong ngi bad ka Elisabet.
NMT_{CD1}	*Ka para* jong nga ka trei kum *u doktor* ha ka hospital jong ngi bad ka, *ka* long kaba bha shibun bad ka bymju riej ïano ïano ruh.
NMT_{CD2}	*Ka para* jong nga ka trei kum *u doktor* ha ka hospital jong ngi , bad *ka* long kaba bha shibun ïa ka dur jong ki .
NMT_{TL1}	*Ka hynmen* jong nga ka trei kum *ka doktor* ha ka bad ka tbit bha ha ka
NMT_{TL2}	*Ka para* jong nga ka trei kum *ka doktor* ha ka hospital jong ngi bad *ka* long kaba bha bad ki.

CONCLUSION

Addressing gender bias in NMT systems is critical to facilitate inclusive and unbiased communication across linguistic barriers. Our study emphasizes the importance of handling gender bias, and the method using data augmentation and transfer learning with the transformer, a cutting-edge architecture as a backbone, has shown promising results. A sizeable gender-balanced dataset is built and presented for the empirical study. Quantitative and qualitative evaluation and analysis are performed on the output of the systems. Qualitative evaluations are performed by two annotators, and the inter-annotator agreement scores show a good correlation of 0.9 for *adequacy*, *fluency* in terms of translation accuracy, and *gender accuracy* for reducing gender bias. The result of the evaluation shows that the models using the data augmentation method performed better in terms of automatic scores for test data $Testset_{CD}$, in *adequacy* as well as in *fluency*. The transfer learning models also show a significant performance in automatic scores with test data $Testset_{GB}$. The NMT_{CD2} model achieved the highest automatic score for test data $Testset_{CD}$, while the models using the transfer learning method, NMT_{TL2} achieved the highest automatic score with the test data $Testset_{GB}$. The statistical evaluation also correlates with automatic scores in the quantitative evaluations. In the case of gender accuracy, the results of the evaluations show that the transfer learning models performed better than the data augmentation models. The output analysis also correlates with the evaluation of gender accuracy. The NMT_{TL2} achieved the highest gender accuracy score despite giving lesser *adequacy* and *fluency* scores compared to other models. In transfer learning, using the English-Khasi gender-balanced dataset for the child model has shown its effectiveness in reducing gender bias. Our method has shown significant results; however, overcoming the challenge of gender bias for English-Khasi language pairs remains a formidable task, indicating that considerable progress is still to be made. Our efforts represent an initial stride towards this objective. In the future, we plan to experiment using different word embedding techniques in the NMT tasks of English-Khasi language pair.

DECLARATIONS

Competing Interest: The authors have no relevant financial or non-financial interests to disclose.

Ethical standards: This work described in this manuscript is original and has not been under consideration for publication elsewhere. All authors read and approved the final manuscript. The research in this manuscript does not involve human participants and animals.

Data availability and access: Data will be made available on reasonable request.

Authors contribution: **Aiusha Vellintihun Hujon**: Conceptualization, Data curation, Methodology, Investigation, Software, Validation, Formal analysis, Writing-Original draft preparation. **Thoudam Doren Singh**: Supervision, Writing - Review & Editing. **Khwairakpam Amitab**: Supervision, Writing - Review & Editing.

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Analysis of Lip Reading of Assamese Digits using Deep Learning

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Abstract—Effective communication in noisy environments, such as aviation, construction, and manufacturing, is often hindered due to auditory challenges, making oral communication difficult. To address this issue, we propose an automatic lip-reading system specifically designed for recognizing Assamese digits in high-noise settings. This study introduces a deep learning-based approach that extracts the geometric features of lip movements from video data to accurately predict spoken digits. Traditional lip-reading models struggle with language-specific nuances due to reliance on generic datasets. To overcome this limitation, we construct a custom dataset of video recordings featuring diverse speakers varying in age, gender, and accent, ensuring a more robust and adaptable model. We employ a CNN+LSTM architecture, where Convolutional Neural Networks (CNNs) capture spatial features, and Long Short-Term Memory (LSTM) networks learn temporal dependencies. Experimental results demonstrate that our CNN+LSTM model outperforms conventional architectures like RNN+LSTM and RNN+CNN, achieving an accuracy of 83%. The findings highlight the effectiveness of deep learning in enhancing accessibility for the deaf and hard-of-hearing and enabling voice-free human-computer interaction.

Keywords: Long-Short Term Memory (LSTM), Lip Region Recognition, Color Imaging, Deep Learning. Lip reading, Assamese language, Custom dataset, Digit recognition.

INTRODUCTION

The importance of lip reading has been increasingly acknowledged, particularly with communication accessibility and technology advancements. Lip reading, the capacity to comprehend speech by analysing the motions of the lips, face, and tongue, has shown to be very beneficial for individuals who are deaf or have hearing difficulties. As technology advances, the potential to enhance lip reading is also evolving via creative methods such as artificial intelligence and augmented reality. In [1] shown that visual cues, such as lip movements, significantly enhance speech comprehension in noisy settings. Their study highlighted the need of integrating visual and auditory input to improve communication, influencing later studies on multimodal speech comprehension. Moreover, [2]

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noted the challenges in distinguishing consonant sounds alone by concentrating on lip motions during visual perception. The study provided significant insights into the limitations of identifying analogous sounds in visual speech perception, contributing to a broader understanding of challenges in visual communication. In [3], investigated the significance of beginning with simpler tasks when training neural networks, emphasising that a progressive escalation in complexity results in improved learning outcomes. The study demonstrated that neural networks exhibit superior performance when initiated with simpler inputs before progressing to more complex patterns, hence enhancing comprehension of cognitive development and the formulation of artificial intelligence systems. [4] were the pioneers in examining the influence of context on the orthography of English vowels, discovering that adjacent letters significantly affected vowel spelling.

Subsequently, [5] demonstrated the enhancement of speech recognition through audio-visual information by comparing three hidden Markov model methodologies: two top-down approaches employing lip contour fitting and PCA, and a bottom-up method grounded in nonlinear scale-space analysis of pixel intensities. [6] suggested a robust model for mouth forms in sign language identification, which is particularly pertinent for the era of lip reading, using deep convolutional neural networks. Mouth forms in sign language are challenging to annotate, and there is a scarcity of publicly accessible annotations. This work uses interconnected information sources to provide inadequate supervision. Subsequently, several writers have conducted study on oral morphology and lip movement [7]. In [8], suggested an innovative deep learning architecture for voice enhancement using lip-reading. It encompasses speech improvement derived from a lip-reading model. The advancement of deep learning and multimodal methodologies has resulted in significant progress in the interconnected domains of lip reading and voice improvement.

Lip reading is essential for tasks such as speech recognition, biometric authentication, and assisting those with hearing impairments, as it involves understanding speech through visual lip movements. Lip reading can be difficult for humans, especially without context, but it helps bridge communication gaps in loud environments and improves comprehension [9]. Recent developments in deep learning have changed the way lip reading is done. Initial attempts, such as the work of [10], brought in deep models, whereas [11] created a complete architecture merging CNNs and LSTMs, boosting accuracy by 6.8%. In this field the progress has been advanced by the presence of extensive datasets like LRW, LRW-1000, LRS2, and LRS3. Nevertheless, the majority of research is centered on English datasets, underscoring the necessity for studies in local languages [12].

The contribution of this research are given below:

(i) A dataset for lip-reading for Assamese digits were generated.

(ii) Pre-process the dataset with different augmentation techniques.

(iii) Build a Deep Neural Network Architecture by comparing different architectures through which the model can predict the digits using the dataset with best accuracy.

The remaining paper consists of the following sections. Literature review on lip-reading identification models are discussed in Section 2. The proposed works and the methodology used are presented in Section 3, the results are discussed in Section 4, Finally, the findings of this work are summarized in Section 5 along with future directions of the work.

LITERATURE REVIEW

In this section, we define the existing work that has been accomplished in the subject modern-day lip analyzing. maximum tactics contain system ultra-modern techniques. After the emergence ultra-modern deep cutting-edge methods, it produced state-of-the-art consequences. Recent progress in lip reading utilizes different neural network structures to improve precision, durability, and practicality in real-life situations.

The recognition of vowels using KNN algorithms was introduced by [13], which transformed the video of the subject articulating vowels into pictures, thereafter selecting images manually for further processing. Nevertheless, other problems such as rapid speech, inadequate pronunciation, insufficient lighting, facial movement, and the presence of beards-moustaches complicate reading of lip. Contour tracking methods and template matching are employed to identify the lips on a face. The K Nearest Neighbor algorithm is utilized to classify images as either “speaking” or “quiet.” The sequence of images is subsequently transformed into segments of speech. A feature vector is calculated for each frame across all segments and stored in the database along with correctly labeled classes. Character recognition is executed via a modified KNN algorithm that allocates more weight to proximate neighbors in [14], that describes techniques for predicting words and sentences from video without audio. We study alternative strategies to use a

VGGNet pretrained on celebrity faces from IMDB and Google Images to handle these picture sequences. The VGGNet is trained on pictures concatenated from numerous frames in each sequence and utilised with LSTMs to extract temporal information. LSTM models fail to outperform other approaches for various reasons, however the concatenated image model with nearest-neighbor interpolation achieved 76% validation accuracy. A lipreading model featuring a well-structured integration and arrangement of processing components to capture highly unique visual features has been detailed in [15]. This highlights the use of a well-organized Deep Belief Network (DBN)-based recognition system. Multi-speaker (MS) and speaker-independent (SI) tasks were performed utilizing the CUAVE database, resulting in phone recognition rates (PRRs) of 77.65% and 73.40%, respectedly. The best word recognition rates (WRRs) achieved in the MS and SI tasks are 80.25% and 76.91%, respectively. The results demonstrate that the proposed method outperforms conventional Hidden Markov Models (HMM) and holds its own against top visual speech recognition methods.

In [16], two distinct deep-learning models for lip-reading were developed: the first model utilised a spatiotemporal convolutional neural network, a bi-gated recurrent neural network, and Connectionist Temporal Classification Loss for video sequences; the second model processed audio by inputting MFCC features into a layer of LSTM cells to produce the output sequence. They furthermore produced a little audio-visual dataset to train and evaluate our algorithm. Their objective was to amalgamate both models to enhance speech recognition in a noisy setting.

An algorithm utilizing a lip deep learning model was proposed in [17] to enhance the accuracy of lip-reading recognition. A binary representation of the lip contour motion sequence was displayed on the spatio-temporal energy, while a dynamic gray-scale of the lips was utilized to reduce noise interference during the recognition phase, significantly enhancing the results of lip-reading recognition thanks to the advanced abilities of deep learning. The results of the experiments suggest that deep learning can extract beneficial features from the dynamic changes in lip gray-scale, leading to better identification results.

A deep learning voice augmentation system based on lip reading was shown [8]. In contrast to benchmarks, the filtering-based approach employs deep learning and analytical audio modelling. Audio-visual (AV) speech augmentation is provided at two levels. Level one uses an innovative deep learning regression model for lip reading. An improved, visually based Wiener filter predicts the second-level clean audio power spectrum for lip-reading. A stacked long-short-term memory (LSTM) regression model for lip reading generates distinct sounds by using temporal visual data from many frames. Utilising inferred speech characteristics, the distinctive filter bank-domain EVWF forecasts intelligible speech spectrums. We evaluate the EVWF against spectral subtraction and log-minimum mean-square error using both ideal and LSTM-driven AV mapping. The suggested AV speech augmentation system is assessed in four dynamic real-world contexts (café, street intersection, public transportation, and pedestrian zone) over a range of low to high signal-to-noise ratios using benchmark grid and ChiME3 datasets. Assessment of restored speech using perceptual quality. Subjective testing utilizes the standard mean opinion score along with inferential statistics. In such simulations, lip-reading and voice enhancement improve speech quality and comprehensibility. A convolutional neural network model is presented in [18] for predicting words based on movies without utilizing any audio. This model is built upon the VGG Net architecture, which has been pretrained on the ImageNet Dataset, with modifications made for the MIRACL-VCl Dataset, which includes 10 words. The model reached 94.86% accuracy in training, 93.82% accuracy in validation, and 60% accuracy in testing. A mobile application has been developed based on this framework, allowing for real-time performance through cloud computing on any smartphone, aiding individuals with hearing impairments in their everyday activities and promoting more natural and spontaneous conversations in a budget-friendly way.

The study [19] presents a way to include facial expression characteristics, namely expression-based and action unit-based data, into the lip-reading technique. Evaluation tests are performed using three public databases: OuluVS, CUAVE, and CENSREC-1-AV. The integration of face expression features has been demonstrated to enhance recognition accuracy across all databases.

In [12], a lip-reading system using neural networks has been introduced to forecast phrases from silent video recordings of individuals conversing. The system is devoid of a language, depending only on visual indicators shown via a restricted set of visemes (unique lip motions). It is designed to accommodate an extensive vocabulary, including hitherto unencountered terms, and exhibits resilience to fluctuating illumination conditions. The technique, validated on the BBC LRS2 dataset, demonstrates markedly enhanced word categorization accuracy relative to leading methodologies.

Subsequently, in [20], the emphasis was placed on the construction of the collection, processing, and data recognition network structure for lip reading. They created a precise and resilient system for lip reading in the study. Initially, they isolated the oral region and segmented it utilising a novel hybrid model incorporating a newly introduced edge and filter. Subsequently, they trained their spatiotemporal model by integrating Convolutional Neural Networks (i.e. CNN) with Bi-directional Gated Recurrent Units (i.e. Bi-GRU). Ultimately, they assessed their algorithm and achieved an accuracy assessment of 90.38%. The outcome demonstrates the efficacy of our system via the use of lip segmentation as inputs to the suggested spatio-temporal model. Our succinct study indicates the want for a suitable model proficient in lip reading Assamese digits. This study introduces a method for identifying lip motions corresponding to Assamese numerals. This section will concisely delineate our intended work and technique.

PROPOSED WORK AND METHODOLOGY

Identifying the Digits uttered by speakers in the Assamese Language. We considered three Architectures and compared their accuracy and training times: (i) A recurrent model using Long Short-Term Memory (i.e. LSTM) (ii) A recurrent model using CNN, and (iii) proposed model i.e. combining CNN and LSTM model. The flow diagram is described in Fig. 1

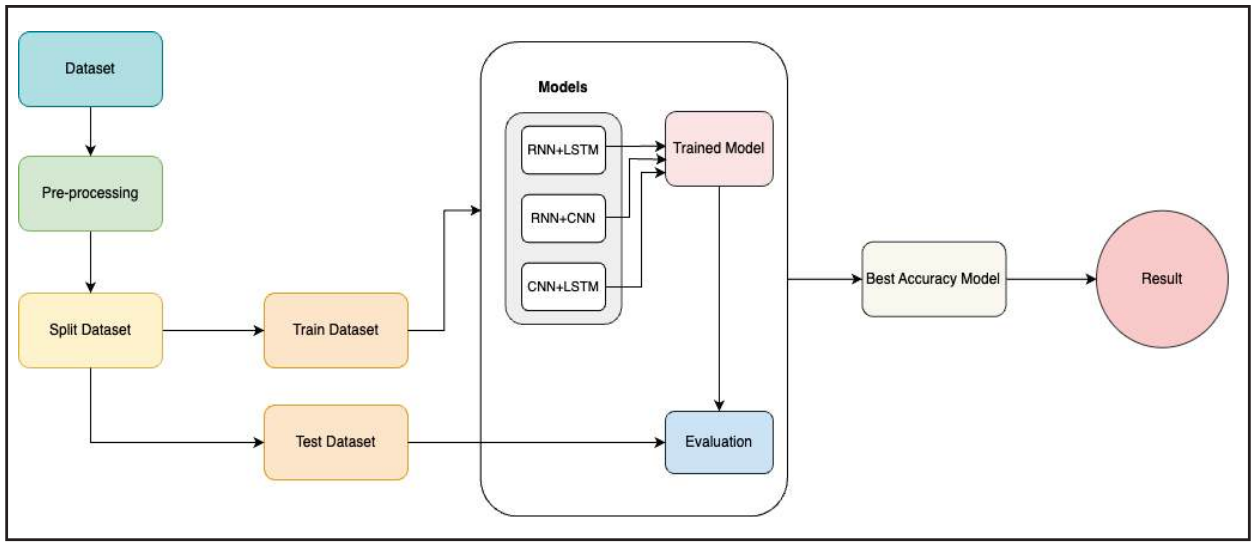

Figure 1: Flow diagram of the Proposed Model

DATA COLLECTION

Deep learning models are trained with a self-compiled dataset because appropriate online datasets or videos are not available. The speakers' excessive movement in online videos made it difficult to detect their lips. As a result, a fresh dataset was formed by 30 volunteers, with speakers saying Assamese numbers from 0 to 10. The dataset contains individuals of different age groups, genders, and accents, ensuring appropriate lighting and stable camera positioning for optimal lip clarity. Methods such as OpenCV and dlib were utilized for extracting and standardizing the lip area in videos, while the dataset comprises 10 categories, with each one corresponding to a numeral. The detailed information on the specifications of the dataset and the number of samples for each digit are reported in Table 1 and in Table 2. The size of the dataset is specified in Table 3.

Table 1: Assamese digits, their transliteration and the number of samples

Digit	Transliteration	No. of Samples
0	xuinno	41
1	ek	80
2	dui	80
3	tini	80
4	sari	80
5	pas	80
6	soy	80
7	xat	80
8	ath	80
9	no	80
10	doh	80

Table 2: Specification of Dataset

Aspect	Specification
Pixels	1920 × 1080
Contents	Digits from '0' to '10'
Number of Speakers	30
FPS (Frames Per Second)	15
Frames Per Video	30
Categories	Facial Expression and Accent
No. of Repetitions	3 times for each digit

Table 3: Size of Dataset

Data	No. of Images
Before Augmentation	2230
After Augmentation	4500
After Data Gain	6200

Data Preprocessing

The acquired dataset is preprocessed to make it suitable for input. It consists of five steps: (a) Video to Frame Conversion; (b) Mouth Localization; (c) Data Cleaning; (d) Image Augmentation; and (e) Concatenating the frames. Using cv2, the video is broken down into frames at a rate of 15 frames per second with a resolution of 1920x1080. The face and lip regions of each frame are identified using dlib's facial landmark detector during processing. The process begins by changing the frame to grayscale, with dlib then detecting 68 facial landmarks. Points 49-68 are related to the area around the mouth, from which the measurements of the lip's height and width are taken, shown in Fig. 2. These measurements serve as attributes for teaching the lip-reading algorithm. The frame-wise information of each digit are shown in Fig. 3.

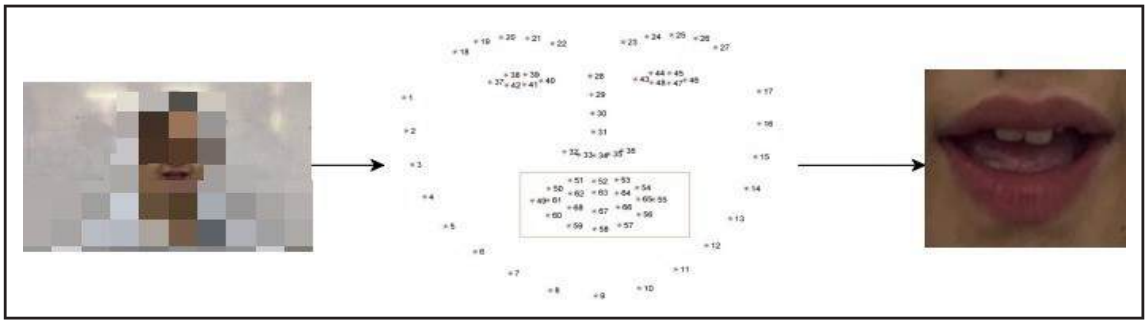

Fig. 2: Lip Detection

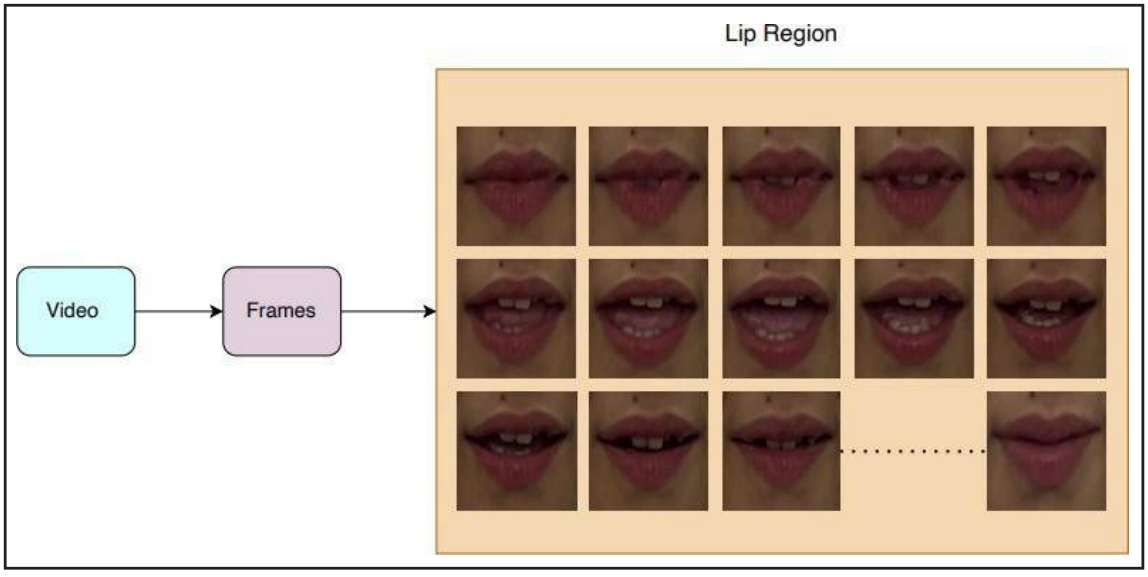

Fig. 3: Detected Lips

Data cleaning is necessary in machine learning in order to eliminate inconsistencies, inaccuracies, and errors that may impact the performance of the model. This involves activities such as standardization, rescaling, identification of anomalies, and filling in missing values. Real-life data can be filled with noise and gaps, and the process of cleaning it guarantees accuracy and dependability. Image augmentation creates synthetic training images using methods such as rotating, flipping, resizing, and adding noise. This increases the volume and variety of the dataset, helping to mitigate overfitting and improve the model's generalization. The enhanced lips are combined into one 224x224 image, in the order of frames. This picture serves as the model's input, containing utterances for every digit that are grouped together and divided into training, validation, and testing groups. The augmentation and concatenated frame representations are shown in Fig. 4, Fig. 5, and Fig. 6.

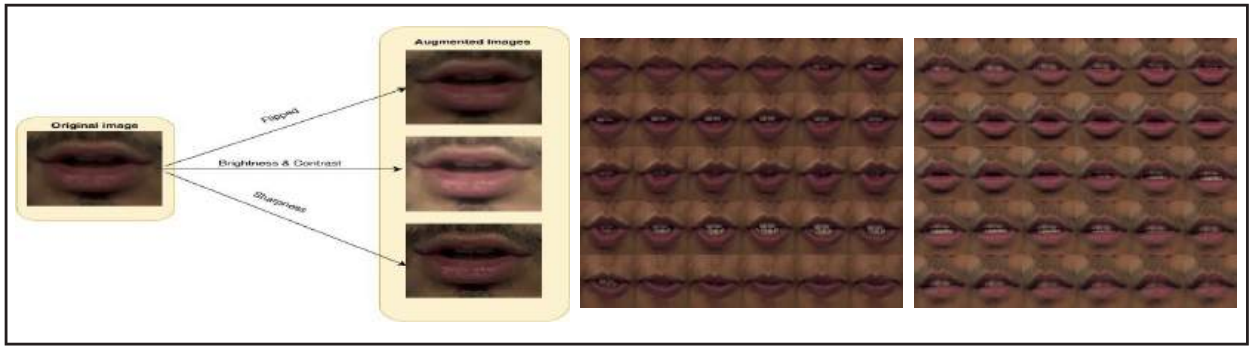

Fig. 4: Augmentation **Fig. 5: Concatenated Frame 1** **Fig. 6: Concatenated Frame 2**

NEURAL NETWORK MODELS

Neural network models are artificial systems that mimic the structure of the human brain, created to identify patterns and forecast outcomes based on data.

A. RNN

A type of neural network, the Recurrent Neural Network (RNN), is specifically created for handling sequential data like time series, natural language, and speech recognition. RNNs differ from traditional neural networks in that they utilize the output of the previous step as input for the current step, enabling them to retain historical data. This is crucial for activities such as anticipating the following word in a sentence, which requires context from earlier words. RNNs' main characteristic is the Hidden State or Memory State, which stores details of the sequence.

Types of RNN Structures Comprise:

- Recurrent Neural Networks (RNN) that go in both directions, known as Bidirectional Recurrent Neural Networks (BRNN)
- GRU stands for Gated Recurrent Units.
- Long Short Term Memory (LSTM) is a type of neural network architecture.

B. LSTM

Long-Short Term Memory (i.e. LSTM), created by [21], is a recurrent neural network (rnn) that aims to capture long-term relationships in sequence prediction tasks such as machine translation, time series forecasting, and speech recognition [22]. In contrast to traditional RNNs, LSTMs utilize a memory cell containing three gates—input, forget, and output gates— that regulate the information flow, enabling the model to choose what information to keep or discard and to efficiently grasp long-term dependencies [23].

C. CNN

CNNs are created for handling data in grid formats, such as images and videos. Three primary layers make up their composition.

- **Convolutional layers:** Convolutional layers utilize filters on input data to identify particular features like edges. The filter moves across the data to create a map displaying the existence of these features.
- **Pooling layers:** Down sampling through pooling helps decrease the dimensionality of feature maps. This assists in decreasing parameters and computations, enhancing efficiency and reducing overfitting. Max-pooling and average-pooling are frequently employed methods.

- **Fully connected layers:** Fully connected layers link each neuron in one layer to every neuron in the following layer, commonly employed in classification scenarios. The feature maps are flattened and moved through these layers to produce probabilities for each class.

- CNNs may consist of activation, dropout, and normalization layers. Parameters are adjusted using gradient descent during their training via backpropagation. CNNs are very successful in tasks related to processing images and videos, such as classification, object detection, and segmentation [24].

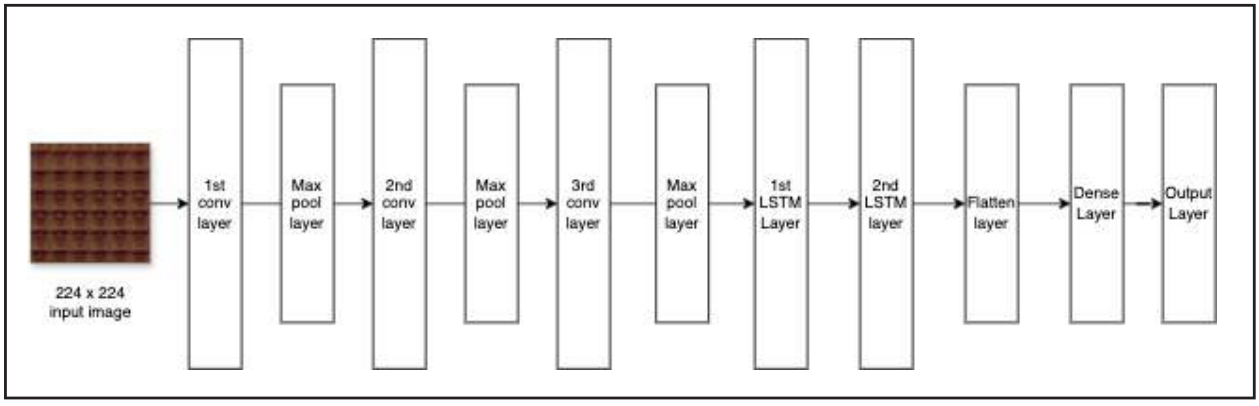

Fig. 7: Classification Process with Model Architecture

D. Model Architecture

Here combining Convolutional Neural Networks (CNN) with Long Short-Term Memory (LSTM) networks we have created the model. The CNN layers focused on extracting spatial features, whereas the LSTM layers were used to capture the temporal relationships in the sequences of lip movements. In this implementation, we included a max pooling layer and applied a dropout rate of 0.2 following the dense layer which contained 374 neurons. For the training process, we configured a batch size of 64 and established a learning rate of 0.001. The model underwent training for 100 epochs while utilizing the RMSprop optimizer. The model's performance on the validation set was monitored after each epoch. The classification process is shown in Fig. 7. The detailed information on Model Architecture with Layers and Output Shapes is reported in Table 4.

Table 4: Proposed model Architecture with Layers and Output Shapes

Layer (Type)	Output Shape
Conv3D	(None, 28, 24, 32, 64)
MaxPooling3D	(None, 9, 8, 10, 64)
Conv3D	(None, 9, 8, 10, 128)
MaxPooling3D	(None, 9, 8, 10, 64)
Conv3D	(None, 9, 8, 10, 128)
MaxPooling3D	(None, 9, 8, 10, 64)
Conv3D	(None, 9, 8, 10, 128)
LSTM (Layer 1)	(None, 9, 8, 10, 128)
LSTM (Layer 2)	(None, 9, 8, 10, 128)
Flatten	(None, 2304)
Dense	(None, 2304)

E. Activation Function

We have used two activation function namely ReLU and softmax. ReLU (Rectified Linear Unit) and Softmax are both commonly used activation functions in neural networks, each with a specific purpose.

Rectified Linear Unit (ReLU): ReLU, also known as Rectified Linear Unit, is an activation function that outputs the input value or zero, whichever is greater. It turns on with positive input and gives out zero for negative input. ReLU allows the model to learn complex relationships by adding non-linearity, which is why it is useful in deep learning. It is efficient in terms of computation and commonly employed in hidden layers to enhance the model's ability to represent information. The function is described as:

$$f(x) = \max(0, x)$$

Softmax: Softmax serves as an activation function employed in the output layer specifically for classification assignments. It converts the final hidden layer's output into a probability distribution, ensuring that the total probabilities add up to 1. The predicted output is chosen from the class with the highest likelihood. Softmax is frequently combined with cross-entropy loss to assist the model in reducing the gap between predicted and actual class distributions. The function is described as:

$$\text{Softmax}(x_1) = \frac{e^{x_i}}{\sum_j e^{x_j}}$$

The overall performance of the model is then evaluated by comparing the results and accuracy from each of the validation and testing units.

RESULTS AND DISCUSSION

Once lip sequences are extracted, the videos are divided into segments, with each segment representing a spoken digit. The lip area is separated using methods in image processing, eliminating unimportant surroundings, and the lip pictures are adjusted for uniformity. After that, every lip sequence is assigned a label matching its digit. In convolutional neural networks, the convolutional layers generate image features using a 3x3 filter size and are often paired with max pooling layers to reduce dimensionality. Next, a feature vector is created for classification by a fully connected layer, where the weights are trained using backpropagation. LSTM networks handle input sequences in a step-by-step manner when dealing with sequential data. Every LSTM cell employs three gates: the forget gate (for discarding data), the input gate (for incorporating new data), and the output gate (for determining output according to the cell state). These gates aid in capturing extensive dependencies by tuning weights through backpropagation during training. The data was into an 80% training set and a 20% testing set to validate. The model was trained using the training set. The combined images were fed into CNN layers to extract features and then passed through max pooling layers to reduce dimensionality. Following three convolutional and max pooling layers, two LSTM layers were used to capture temporal patterns in the output. In the end, the result was inputted into two fully connected layers prior to reaching the output layer.

Validation and Testing

To prevent overfitting and enhance model performance, 10% of the dataset was reserved for validation during training. Validation accuracy was monitored by evaluating the softmax activation function after each batch, allowing for necessary hyperparameter adjustments. This approach ensured that the model remained robust, avoiding excessive specialization and enabling it to generalize effectively to new data. Following the training phase, 20% of the dataset was allocated for testing to assess the model's final performance. Maintaining a consistent batch size throughout training was crucial for ensuring stable and effective learning. The model's ability to generalize to fresh data was evaluated using validation accuracy tracked through the softmax function. The study compares the performance of three different models RNN+LSTM, RNN+CNN, and the proposed CNN+LSTM model-based on test accuracy, class count, kernel size, and the number of training epochs, as reported in Table 5. The CNN+LSTM model achieved the highest accuracy (83%), outperforming both RNN+LSTM and RNN+CNN. This indicates that integrating CNN for feature extraction with LSTM for sequence learning provides a more robust solution for automatic lip-reading. This hybrid approach proves particularly effective in handling the unique challenges of recognizing Assamese digits in noisy environments. With an accuracy of 83%, the model is now ready for real-time deployment, offering a reliable solution for interpreting lip movements in challenging acoustic conditions.

Confusion Matrix

A confusion matrix evaluates a classifier's performance by organizing predictions into False Positives (FP), True Positives (TP), False Negatives (FN), and True Negatives (TN) [14]. Figure 8 represents the Confusion Matrix for LSTM (Lip Reading of Digits (0-9)).

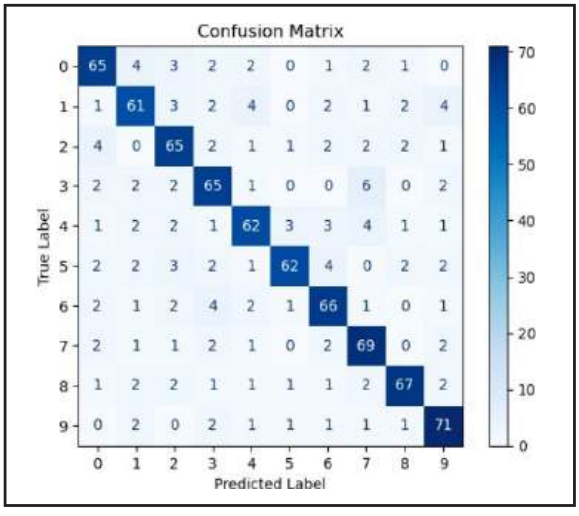

Fig. 8: Confusion Matrix for LSTM (Lip Reading of Digits (0–9))

Table 5: Model with Accuracy

Model	Test Accuracy	Class	Kernel Size	Epochs
RNN+LSTM	76%	10	3x3x3	100
RNN+CNN	68%	10	3x3x3	100
Proposed (CNN+LSTM)	83%	10	3x3x3	100

Analysis Between Accuracy Curve and Loss Curve

The loss curve and accuracy curve of proposed method are shown in Figs. 9, and 10. Form Fig. 9, the training and validation loss decreasing steadily over epochs, indicating effective model learning. The small gap between the curves suggests minimal overfitting and good generalization to unseen data. The consistent downward trend implies the model is improving with more training. Similarly, from Fig. 10 shows training and validation accuracy steadily increasing over epochs, indicating improved model performance. The training accuracy remains slightly higher than validation accuracy, but the small gap suggests minimal overfitting and good generalization. The upward trend demonstrates effective learning.

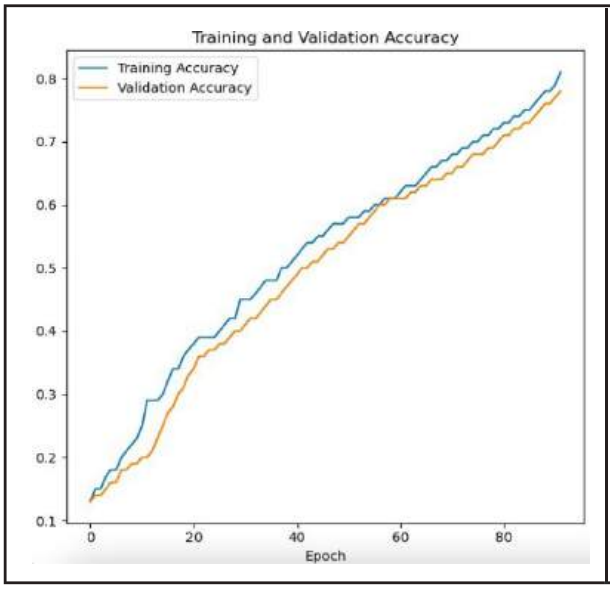

Fig. 9: Accuracy Curve

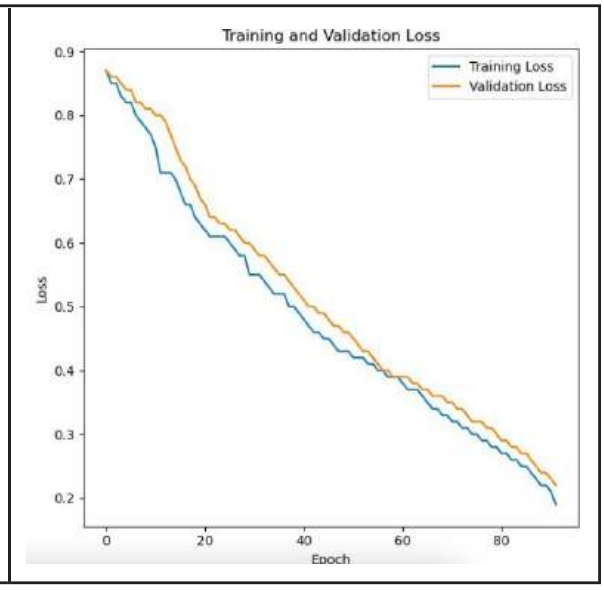

Fig. 10: Loss Curve

CONCLUSION AND FUTURE DIRECTIONS

Our research on lip-reading Assamese numbers demonstrates significant progress in understanding language signals within a regional context. By leveraging a custom CNN+LSTM model and a self-collected dataset, we establish the feasibility of applying lip-reading technology to regional languages. A comparative analysis of different models RNN+LSTM, RNN+CNN, and CNN+LSTM reveals that the proposed CNN+LSTM model outperforms the others with an accuracy of 83%. The integration of CNN for spatial feature extraction and LSTM for temporal dependency learning proves to be the most effective approach for recognizing Assamese digits in noisy environments. This study holds promising implications for improving accessibility, particularly for deaf and hard-of-hearing individuals, enabling them to understand spoken Assamese digits without relying on sound. Additionally, it enhances human-computer interactions, paving the way for voice-free command execution in Assamese. These advancements contribute to the broader goal of inclusive communication technologies, making digital interactions more accessible across diverse linguistic and auditory needs.

This study establishes a strong foundation for future advancements in lip-reading technology. Future research

can explore pre-trained models or develop customized neural network architectures to further enhance accuracy. Expanding the dataset in both size and diversity will improve the model's generalization, making it more robust for wider applications and diverse users. Our findings underscore the crucial role of deep learning in advancing lip-reading technology and highlight the importance of transfer learning for multilingual adaptability. Extending these advancements to other languages will contribute to a more inclusive and accessible technological landscape, broadening the impact of lip-reading solutions in real-world scenarios.

CONFLICTS OF INTEREST

No conflict of interest was declared by the authors.

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Machine Learning Model to classify on Metformin-Responders and Metformin-non-Responders of Type-II Diabetes Mellitus from Whole Exome Data in Mizo Population

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Abstract—Type-II Diabmetes Mellitus has emerged as one of the most significant global health crises of the century. The advancement of bioinformatics has made it easier to analyse complex biological data, while machine learning has become increasingly viable due to the vast availability of such data. It can uncover hidden patterns within biological datasets, aiding in disease prediction, diagnosis, and pharmacological treatment. This study pioneers the classification of Metformin-Responders and Metformin-Non-Responders in Type-II Diabetes Mellitus patients using Machine Learning based on whole exome sequencing data. Data samples were collected with informed consent from confirmed diabetic patients of Mizo ethnicity with a strong familial history of the disease. Four ensemble models—Adaptive Boosting, Gradient Boosting, Extreme Gradient Boosting, and Random Forest—were employed for classification. Among these models, the Random Forest classifier demonstrated the highest performance, achieving an accuracy of 96%, an F1-score of 96%, precision of 96%, recall of 96%, and a Receiver Operating Characteristic score of 98%, with a misclassification rate of 3.8%. This study fosters interdisciplinary knowledge transfer between computer scientists, biologists, and clinicians, demonstrating that Machine Learning models are highly reliable for classifying Metformin-Responders and Metformin-Non-Responders in Type-II Diabetes Mellitus patients based on whole exome data.

Keywords: Machine Learning: Features Extraction, Test and Train Accuracy, Type-II Diabetes Mellitus, Whole exome sequencing.

INTRODUCTION

Artificial Intelligence (AI) encompasses systems designed to perform tasks that typically require human intelligence, such as problem-solving and decision-making (Abrahams. 2025, Wang. 2019). Within AI, Machine Learning (ML) focuses on enabling machines to learn from data and improve their performance over time without explicit programming (LeCun *et al.* 2015). It is particularly transformative in clinical medicine, as it enables automated interpretation of complex, multidimensional health data—such as medical imaging, genomic sequences, or electronic health records (EHRs)—to support diagnosis, prognosis, and treatment planning (Topol. 2019). A foundational requirement for

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effective ML in healthcare is the use of expert-labelled training data, where clinicians annotate datasets with diagnostic, prognostic, or therapeutic metadata. This supervised learning process allows ML models to identify subtle correlations within the data, empowering them to classify diseases (e.g., cancer subtypes), detect anomalies (e.g., tumors in radiology), or predict clinical outcomes (e.g., sepsis risk) with high accuracy (Raspurkar *et al.* 2022, Esteva *et al.* 2017)

As reported by the World Health Organization (WHO), diabetes is the seventh leading cause of mortality worldwide, responsible for approximately 2 million deaths annually, with its burden disproportionately affecting low- and middle-income countries (WHO, 2023). Beyond mortality, DM imposes substantial socioeconomic strain, with global healthcare expenditures exceeding $966 billion in 2021 due to direct medical costs and productivity losses (IDF, 2021). Meanwhile, Type-II Diabetes Mellitus (T2DM) constitutes over 90% of global diabetes cases, affecting approximately 537 million adults aged 20–75 years, with projections 3 suggesting a rise to 783 million by 2045 (Chatterjee *et al.* 2017, Patgiri *et al.* 2021).

Mizoram also faces rising non-communicable diseases (NCDs), including Type-II Diabetes Mellitus (T2DM), linked to rapid urbanization, dietary shifts, and genetic predisposition (Brindha *et al.* 2022). Mizoram, one of India's eight northeastern states, is a mountainous region bordered by Myanmar to the east and south, Bangladesh to the west, and the Indian states of Assam, Manipur, and Tripura to the north. Known for its lush green hills, dense forests, and vibrant cultural heritage, Mizoram is home to the Mizo people, a Tibeto-Burman ethnic group with a distinct identity shaped by history, language, and traditions (Lalthlamuana, 2021) and has an independent ethnic identity (Lalrohlui *et al,* 2021). It has reported that the number of T2DM patients is steadily increasing as per the record found in various hospital and clinic. In the Mizo population, a nucleotide change (A/T) at position 274 has been identified in YTHDC2, resulting in an amino acid substitution from Tyrosine (Y) to Phenylalanine (F). This mutation occurs within the Helicase ATP-binding domain, introducing an amino acid with different properties, which may disrupt the domain's structure and potentially impair its function (Freda *et al,* 2021).

This research utilizes Deoxyribonucleic Acid (DNA) sequencing as a diagnostic tool. Whole Exome Sequencing (WES), a DNA sequencing-based technique, has gained considerable attention among bioinformatics researchers for its ability to process large-scale biological datasets and extract diverse genomic features. By targeting exonic regions—the protein-coding segments of the genome—WES facilitates the identification of coding variants associated with various diseases (Ng Sarah *et al.* 2010). Additionally, Artificial Intelligence (AI) techniques can be employed to efficiently handle vast amounts of biological data and uncover hidden patterns within genomic datasets (El-Attar *et al.* 2022).

The main contribution of this study is the development of a classification model based on a whole exome dataset using four ensemble techniques: Random Forest (RF), Extreme Gradient Boosting (XGBoost), Gradient Boosting, and Adaptive Boosting (AdaBoost). In particular, the RF model is designed to classify genomic data into Metformin and Metformin non responder of T2DM groups.

RELATED WORK

Type-II Diabetes Mellitus (T2DM) is a multifactorial disease influenced by both environmental and genetic factors. Metformin remains the first-line pharmacotherapy for T2DM due to its efficacy in lowering blood glucose levels, cost-effectiveness, and safety profile. However, significant inter-individual variability in metformin response has been documented. Approximately 30–40% of patients may not achieve optimal glycaemic control with metformin monotherapy (Shu *et al.* 2007, Zhou *et al.* 2009). This variability has prompted investigations into the underlying genetic determinants that might predict treatment outcomes.

The study conducted by (McCarthy *et al.* 2008) revealed that Whole exome sequencing (WES) has emerged as a powerful tool to identify rare and common variants that contribute to the pathogenesis of T2DM and its treatment response. Unlike genome-wide association studies (GWAS), which are limited to common variants, WES can capture the full spectrum of coding variants, offering deeper insights into the molecular mechanisms underlying drug response in diverse populations, including those in Northeast India, WES has the potential to uncover population-specific variants that may not be represented in larger, predominantly European cohorts.

A system on the integration of ML models with genomic data has been developed by (Libbrecht *et al*, 2015), that has opened new avenues for personalized medicine. ML models such as support vector machines, RFs, and deep neural networks have been applied to high-dimensional

genomic datasets to predict disease risk and drug response. These algorithms can learn complex patterns from whole exome data, enabling the classification of individuals into MR and MnR. The success of these methods in other pharmacogenomic contexts supports their potential application in T2DM, where multiple genetic variants may interact to influence metformin efficacy.

The authors at (Lalrohlui, *et al.* 2021) had found that various new gene variants were observed for Mizo population from a set of 582 T2DM-associated genes extracted from the GWAS catalogue, 202 variants were identified as disease-causing. Among these, 142 were located in intronic regions and 8 in exonic regions. Moreover, several novel gene variants—specifically in YTHDC2, PINX1, KCNQ1, TNRC6A, TACO1, LAMA1, and ACP7—were discovered in the Mizo population, with all T2DM samples exhibiting these variants and suggesting that these genetic differences could also impact MR.

As mentioned in this related work, some researchers analysed data exclusively from MR, excluding non-responders, while others focused on identifying the most suitable medication for individualized treatment. Some studies included the 30–40% of patients who did not achieve optimal glycaemic control with metformin monotherapy. Additionally, GWAS were used to investigate genetic factors; however, GWAS primarily targets common variants and is often biased toward European populations, limiting its applicability to diverse groups such as those in Northeast India (Popejoy *et al*., 2016). In contrast, this study utilized Whole Exome Sequencing (WES) as a classification approach, offering the advantage of capturing both common and rare variants, particularly in underrepresented populations (Karczewski, *et al.* 2020). The dataset used in this study included genomic data from both T2DM-positive and T2DM-negative individuals.

EXPERIMENT AND DISCCUSION

Samples Collection

This study includes T2DM patients with a strong familial history and healthy controls from the Mizo ethnic tribe. Samples were collected five years post-diagnosis and confirmed by a diabetologist. Both case and control participants were aged between 40 and 50 years. The T2DM cases were unrelated individuals, while the control group comprised randomly selected healthy blood donors from the same population.

T2DM diagnosis followed 5 the World Health Organization Expert Committee guidelines (WHO, 2003), and all samples were obtained with informed consent from participants. Inclusion criteria for T2DM cases required fasting plasma glucose levels exceeding 120 mg/dL and post-prandial plasma glucose levels above 200 mg/dL, as detailed in Supplementary Table 1. Genomic DNA was extracted from blood samples using the methodology in (Ghatak *et al.* 2013).

Table 1: Details of Added Features

Features	rsid	Details	MnR	MR
SNP1	rs1800450(Mannose Binding lectin) + rs10509305 (Preeclampsia /eclampsia 4)	• MBL -positive correlation with HbA1c • MBL with development of cardiovascular complications in type 2 diabetics - a positive association of MBL with TG to HDL-C ratio • Strong biomarker for diabetic retinopathy Diabetes during pregnancy develops pre-eclampsia	4/9	2/9
SNP2	rs1801131 (methotrexate response Toxicity - MTX)	• Like metformin, MTX decreases intestinal absorption of glucose and increase insulin sensitivity	2/9	5/9
SNP3	rs1801131 + rs147487242 (ARPKD)	• Autosomal recessive polycystic kidney disease	Not present	4/9
SNP4	rs147487242 + rs116065504	Autosomal dominant epilepsy	Not present	3/9
SNP5	rs17848485 + rs200585150	Hereditary fructosuria	3/0	Not present

(Table 1 Contd. ....)

(.... Contd Table 1)

SNP6	rs6929137	Associated with diabetes type 2 and glycemic traits. Estrogen resistance	9/9	8/9
SNP7	rs117934093 (Cohen syndrome) + rs2229813 (Autosomal recessive Alport syndrome)	Cohen syndrome ARAS may attribute to diabetes	5/9	Not present
SNP8	rs140056980	Cardiovascular phenotype Metformin treatment associated with marked reduction in the relative risk of the major adverse cardiac events	3/9	Not present
SNP9	rs150385900	Cardiomyopathy	Not present	2/9

The DNA quality was assessed via agarose gel electrophoresis, and quantification was performed using a Bio spectrophotometer (Eppendorf, Hamburg, Germany).

The newly identified SNPs from this population are expected to have a similar impact on the disease and can be validated through SNP-based prediction and classification (Soki *et al.* 2016, Nicholas *et al.* 2019). To strengthen our dataset, additional SNPs with significant associations to MR and MnR were incorporated, derived from Next-Generation Sequencing (NGS) data. The details of the newly added features, including feature names, rs-IDs, descriptions, MR, and MnR, are presented in Table 1.

Whole Exome Sequnce (WES) Analysis

WES facilitates the identification of both rare and common genetic variants, offering valuable insights into the molecular mechanisms underlying T2DM and their influence on treatment responses. This approach strengthens dataset reliability and contributing to treatment outcomes. Genomic DNA was extracted from the diabetic patient blood samples (Ghatak *et al.* 2013) and WES (100X coverage) was conducted in Illumina NovaSeq 6000. The data analysis was performed using the in-house developed automated tool WEAP (Ranjan *et al,* 2023) (https://github.com/ranjanjs34/weap).

The sequenced data was conducted such as Raw sequencing reads in FASTQ format are generated and subjected to quality control using FastQC (Andrew *et al.* 2010). Low-quality regions and adapters are trimmed using Trimmomatic (Bolger *et al.* 2014). The cleaned reads are then aligned to a reference genome using alignment tools such as BWA or Stampy, producing SAM files that store alignment data (Lunter *et al.* 2011). Next step involves File Conversion and Processing, SAM files are converted to sorted BAM files using Samtools (Li *et al.* 2009).

Duplicate reads are marked and removed using Picard to ensure high-quality data (Picard-Kit, 2010). Variant Calling: Variants, including SNPs and indels, are called from the processed BAM files using variant calling tools. The output is stored in a VCF (Variant Call Format) file, which contains information about the discovered variants (Rimmer *et al.* 2014).

Annotation

Annovar used to determine their functional and clinical relevance. This step links variants to databases such as ClinVar and dbSNP, (Wang *et al.* 2010). Filtering, Low-quality variants are filtered out, and biologically significant variants are prioritized. Population frequency data from databases like gnomAD (Karczewski *et al.* 2019) are used to assess variant prevalence and potential pathogenicity. This ensures that only high-confidence, clinically relevant variants are retained for further analysis.

Data Preprocessing

Data preprocessing is a crucial step in medical data classification, data analysis and ML pipeline. Since medical data often contains missing values (García *et al.* 2010), imbalanced classes (He *et al.* 2009), high-dimensional features (Saeys *et al.* 2007), and elimination duplicate/ redundant data (Cios *et al.* 2002), proper preprocessing can significantly improve model performance.

Handing Redundant Data

To ensure the dataset is clean and concise, it is essential to remove such data. This process is typically carried out using libraries like Pandas for handling duplicate data and NumPy or scikit-learn for addressing redundancy. The function $f(D)$ represents the process of removing duplicate rows while keeping only the first occurrence in the Eqn. (1):

$$f(D) = \{r_i \in D \mid \forall j \neq i,\ r_i \neq r_j \quad (1)$$

Where the condition $\forall j \neq i$, r_i *ensures that only the first occurrence of each unique row is retained, removing subsequent duplicates.*

Redundant data are columns that provide no additional information because they are linearly dependent on other features (Cyon *et al.* 2003). If two features X_i and X_j have high correlation ($\rho(X_i, X_j) \approx 1$), then one is redundant and removed using Eqn. (2).

$$(\rho(X_i, X_j) = \frac{\mathrm{Cov}(X_i, X_j)}{\sigma X_i, \sigma X_j} \quad (2)$$

where σX_i *and* σX_j *are the standard deviations of* X_i *and* X_j.

Handling Missing Values

In this experiment, we used the imputation method to handle missing values which replace missing values with the mean. While there are other statistical measures for handling missing data, such as the median, mode, or a constant value, mean imputation was chosen as it tends to outperform the other methods in this context. To compute the mean values, the summation function presented in Eqn. (3) and (4) is used to replace missing values for imputation. For a feature $X_j = \{x_{1j}, x_{2j}, \ldots, x_{jn}\}$, compute the mean:

$$\bar{x}_j = \frac{1}{n}\sum_{i=1}^{n} x_{ij} \quad (3)$$

Replacing missing values with $\bar{x}_j$:

$$x_{ij} = \bar{x}_j, \ \forall i \ where \ x_{ij} = NaN \quad (4)$$

Handing Imbalance Data

Synthetic Minority Over-sampling Technique (SMOTE) was employed in this experiment to handle imbalance class. The authors at (Nitesh. 2002) demonstrated that SMOTE outperforms other methods like random oversampling and undersampling in terms of improving classifier performance on imbalanced datasets. We generate new sample using interpolation in Eqn. (5). To form balance data, matric base calculation was conducted to combine original and synthetic sample shown in Eqn. (6).

$$x_{synthetic} = x_i + \lambda . (x_j - x_i) \quad (5)$$

where x_j is a *k*-nearest neighbor of x_i and λ is a random number in the range [0, 1].

$$X_{balanced} = \begin{vmatrix} X_{majority} \\ X_{minority} \\ X_{synthetic} \end{vmatrix}, Y_{balanced} = \begin{vmatrix} Y_{majority} \\ Y_{minority} \\ Y_{synthetic} \end{vmatrix} \quad (6)$$

Where, $X_{majority} \in \mathbb{R}^{n_{majority}\ X\ p}$, $X_{minority} \in \mathbb{R}^{n_{minority}\ X\ p}$, $X_{\text{synthetic}} \in \mathbb{R}^{n_{synthetic}\ X\ p}$ *and* ^{n}*synthetic = is chosen such that* ^{n}*majority* ≈ ^{n}*minority* + ^{n}*majority*.

Feature Fngineering

The initial dataset consisted of 85 columns. Following the removal of duplicates and redundant data, the number of columns was reduced to 65. To further refine the dataset, feature selection was performed. In this study, the ridge regression method was employed, as it is a robust technique for extracting feature importance, particularly in high-dimensional datasets with multicollinearity. Its ability to shrink coefficients while retaining all features makes it particularly useful for understanding the relative importance of predictors in complex models (Saeys *et al.* 2007). Ten most and least significant was selected from the 65 features. Features are standardized to have a mean of 0 and a standard deviation of 1 using the formula in Eqn. (7).

$$z_{ij} = \frac{x_{ij} + \mu_{ij}}{\sigma_j} \quad (7)$$

Where: Z_{ij} *is the standardized value of feature j for sample i. This is the transfor*^{m}*ed feature value after standardization.* x_{ij} *is the original value of feature j for sample i before standardization.* μ_j *: is the mean (average) of feature j across all samples.* σ_j *is the standard deviation of feature j across all samples.*

A Ridge Regression model is trained to predict the target variable.

Kernel Density Estimation (KDE) is used to estimate the probability density function (PDF) of each feature's distribution for responders (y = 1) and non-responders (y = 0). The KDE is calculated in Eqn. (8).

$$\hat{f}_h(x) = \frac{1}{nh}\sum_{i=1}^{n} K\left(\frac{x - x_i}{h}\right) \quad (8)$$

Where: $\hat{f}_h(x)$ *: Estimated PDF at point* x, n*: Number of samples, h : Bandwidth parameter (controls smoothness),* K(.)*: Kernel function.*

Label Encoding

The original dataset consists of categorical data which have to converted into numerical number using label encoding.

Label encoding is a fundamental preprocessing step in ML when dealing with categorical data. It transforms categorical variables into numerical representations, enabling algorithms to process and learn from the data effectively (Zheng *et al.* 2018). This experiment performs label encoding on four categorical columns of the dataset such as chr, Ref, Alt and Gene.refGene.

PROPOSED METHODOLOGY

The proposed classification model for predicting type-II diabetes mellitus utilizes four ML algorithms: RF, AdaBoost, Gradient Boosting, and XGBoost. Dataset were randomly divided into 70 % for training and 30% of data was reserved for test data. This section provides a detailed explanation for each algorithm individually. Fig 1 illustrates the overall structure of the proposed approach.

ADABOOST (ADAPTIVE BOOSTING)

The AdaBoost classification model utilized in this study is the combination of multiple weak learners (usually decision stumps, i.e., shallow decision trees with one split) into a strong learner (Freund *et al.* 1997). The algorithm works by iteratively training weak learners on weighted versions of the dataset, where misclassified samples are given higher weights in subsequent.

The AdaBoost classification model utilized in this study is the combination of multiple weak learners (usually decision stumps, i.e., shallow decision trees with one split) into a strong learner (Freund *et al.* 1997). The algorithm works by iteratively training weak learners on weighted versions of the dataset, where misclassified samples are given higher weights in subsequent iterations. The final prediction is made by combining the predictions of all weak learners, typically using a weighted voting scheme. In the experiment, we used n_estimators that controls the number of weak learners (decision stumps) used in the ensemble and learning_rate to controls the contribution of each weak learner to the final model. We Compute the weighted error using Eqn. (9) as it is a key concept in AdaBoost model, where it measures how well a weak learners on weighted versions of the dataset, where misclassified samples are given higher weights in subsequent iterations. The final prediction is made by combining the predictions of all weak learners, typically using a weighted voting scheme. In the experiment, we used n_estimators that controls the number of weak learners (decision stumps) used in the ensemble and learning_rate to controls the contribution of each weak learner to the final model. We Compute the weighted error using Eqn. (9) as it is a key concept in AdaBoost model, where it measures how well a weak learner performs on the training data (Freund *et al.* 1997) taking into account the weights assigned to each sample, and the final prediction is calculated using the Eqn. (10).

$$\epsilon_t = \sum_{i=0}^{N} w_i^{(t)} . I(h_t(x_i) \neq y_i) \quad (9)$$

$$H(x) = sign \sum_{t=1}^{T} \alpha_t . h_t(x) \quad (10)$$

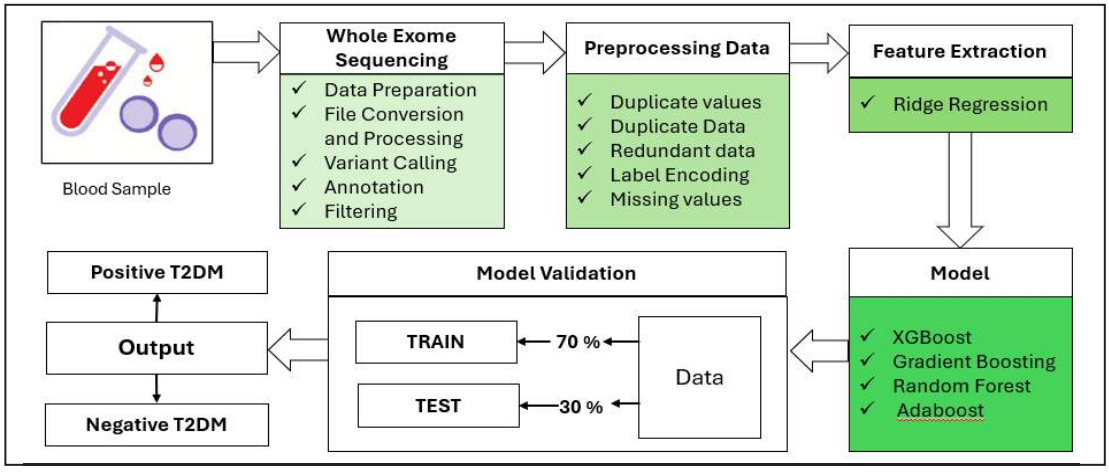


Fig 1: Systematic view of Proposed Model

Gradient Boosting

Another classification model used in this study is Gradient Boosting that builds an ensemble of decision trees sequentially. Unlike AdaBoost, Gradient Boosting minimizes a loss function (e.g., mean squared error for regression or log loss for classification) by fitting new trees to the residuals (errors) of the previous trees (Freidman. 2001). We trained each tree to correct the mistakes of the previous trees, and the final prediction is the sum of the predictions from all trees. We implement the code n_estimators to number of decision trees in the ensemble, learning_rate to shrinks the contribution of each tree to prevent overfitting and max_depth: Maximum depth of each decision tree. The final prediction is calculated as in Eqn. (11).

$$F_T(x) = F_0\,(x) \; + \sum_{t=1}^{T} \eta . h_t(x) \qquad (11)$$

Random Forest

RF is a bagging (bootstrap aggregating) algorithm that builds an ensemble of decision trees trained on random subsets of the data and features (Breiman. 2001). In this study, each tree is trained independently, and the final prediction is made by averaging the predictions of all trees (for regression) or taking a majority vote (for classification). n_estimators was used to count number of decision trees in the forest, max_depth is to count maximum depth of each tree. Limiting the depth helps control overfitting, and lastly, we also imlemented min_samples_split to fetch the information of minimum number of samples required to split an internal node. For classification model, we combined classification formula as in Eqn. (12) and regression formula as in Eqn. (13) to produce a fine result. A satisfactory result can be obtained comparing to others models.

$$H_x \; = \; mode\,\{h_1(x), h_2(x), \ldots, h_T(x)\,\} \qquad (12)$$

$$H_x = \frac{1}{T} \sum_{t=1}^{T} h_t(x) \qquad (13)$$

XGboost (Extreme Gradient Boosting)

This classification model introduces several enhancements for better performance and scalability (Chen *at al.* 2016). We performed regularization model for formalization to control overfitting and supports parallel processing for faster training. Hyperparameter tunning is employed using randomized search, such as n_estimators to number of decision trees in the ensemble, learning_rate to controls the contribution of each tree to the final model max_depth to Maximum depth of each tree. Calculation is performed base on the equation in Eqn. (14) for final prediction.

$$F_T(x) \; = F_0(x) \; + \sum_{t=1}^{T} \eta . h_t(x) \qquad (14)$$

Each model was optimized via hyper-parameter tuning using Randomized-Search-Cross Validation technique that having four dimensions with maximum number of 200. Three-fold cross validation also utilized to ensure generalization and it is the best fit cross validation for this study. To access the performance of the proposed RF model, experiment based on whole exome data against XGboost, Gradient Boosting, Adaboost are performed.

The evaluation metrics used in this study are Accuracy, F1 Score, Precision, Recall (sensitivity), ROC AUC (Receiver Operating Characteristic - Area Under Curve). These matrices are calculated by Eqn. (15)-(19) respectively (Powers *et al.* 2020) and Kernel Density Estimate (KDE) plots are used to show the probability density of each feature for the two groups. As KDE is a non-parametric way to estimate the probability density function (PDF) of a random variable. KDE plots are particularly useful in data visualization and exploratory data analysis because they provide a smooth, continuous representation of the underlying distribution of data (Duong. 2007) and calculated as in Eqn. (20).

$$Accuracy \; = \; \frac{TP \; + \; TN}{TP \; + \; FP \; + \; TN \; + \; FN} \qquad (15)$$

$$F1\;Score \; = \; \frac{2TP}{2TP \; + \; FP \; + \; FN} \qquad (16)$$

$$Precision \; = \; \frac{TP}{TP \; + \; FP} \qquad (17)$$

$$Recall\;(Sensitivity) \; = \; \frac{TP}{TP \; + \; FN} \qquad (18)$$

$$AUC \; = \; \int_0^1 TPR(t)\; d(FPR(t)) \qquad (19)$$

$$F_T(x) \; = F_0(x) \; + \sum_{t=1}^{T} \eta . h_t(x) \qquad (20)$$

Where: n: *Number of data points.* x_i *:Individual data points. K(u) : Kernel function. h : Bandwidth parameter controlling the smoothness of the estimate.*

To run the proposed model successfully Python Jupiter Notebook Version 3 was implemented, with the subset of learning packages -Scikit-learn (version-1.2.2). To display graphical imagematplotlib (version-3.8.0) and Seaborn (version-0.12.2) were integrated, for data preprocessing and interpretation technique we used numPy (version-1.26.4), pandas (version-2.1.4), and Imbalanced-learn (version-0.11.0) (Hunter. 2007).

RESULT AND DISCUSSION

Feature Selection

In this study, feature selection is conducted using Ridge Regression (RR) with a maximum of 10,000 iterations, ensuring optimal quality for this work. The ten most significant and least significant features are detailed in Table 2 and Table 3, respectively. Classification is performed based on these selected features, all of which play a crucial role in the classification process. A graphical representation of these extracted features is also illustrated in Fig. 2, displaying indicator scores in a bar chart. A higher bar value signifies a greater impact in both cases.

Table 2: Ten Most Significant Features

FEATURE NAME	DESCRIPTION
AF_amr	Allele Frequency in the American (AMR) population.
SNP2	A specific Single Nucleotide Polymorphism (SNP)identifier or feature.
AF_eas	Allele Frequency in the East Asian (EAS) population.
SNP3	Another specific SNP identifier or feature.
AF_oth	Allele Frequency in the Other (OTH) population.
AF_Female	Allele Frequency in the female subset of the population.
SNP4	Another specific Single Nucleotide Polymorphism (SNP)identifier or feature.
ALL.sites. 2015_08	A dataset indicating all genomic sites analysed as of August 2015.
ExAC_OTH	Allele Frequency in the Other (OTH) population from the ExAC-database.
AF_nfe	Allele Frequency in the Non-Finnish European (NFE)population.

Table 3: Ten Least Significant Features

FEATURE NAME	DESCRIPTION
SNP7	A specific **SNP** identifier or feature.
ExAC_FIN	Allele Frequency in the **Finnish (FIN)** population from the **ExAC**database.
SNP6	Another specific **SNP** identifier or feature.
ExAC_AFR	Allele Frequency in the **African (AFR)** population from the **ExAC-**database.
LRT_Score	Likelihood Ratio Test (LRT) score for predicting whether a variant is deleterious.
ExAC_NFE	Allele Frequency in the female subset of the population.
AF_afr	Another specific Single Nucleotide Polymorphism (SNP)identifier or feature.
SNP5	A dataset indicating all genomic sites analysed as of August 2015.
ExAC_ALL	Allele Frequency in the Other (OTH) population from the ExAC-database.
non_topmed _AF_popmax	Allele Frequency in the Non-Finnish European (NFE)population.

Kernel Density Estimation (KDE) Plots

As mention in earlier statement that KDE shows the probability density of each feature for the two groups. The blue curve corresponds to class 0, while the red curve represents class 1. The Fig. 3 indicates density distributions on ten most significant feature that has clear separations between the target classes, meaning they strongly contribute to the predictive model.

The Fig. 4 displays density distributions on ten least significant, overlapping curves indicate weak discriminatory power. In most of these plots, the two distributions overlap significantly, indicating that there is no strong separation between the two classes with respect to these features – SNP7, SNP6, LRT_score, AF_afr, ExAC_ALL. This suggests that these features may not contribute meaningfully to distinguishing between the two classes and could be less informative for classification purposes.

Models Comparison

The RF model demonstrated the highest accuracy among all the models evaluated in this study as shown in the Fig. 5 and Fig. 6. Notably, no signs of overfitting or underfitting were detected. The hyperparameter tuning process for the hidden layers involved the following configurations:

1. n_estimators: [50, 100, 150]
2. max_depth: [None, 2, 4, 6, 8]
3. min_samples_split: [2, 5, 10]

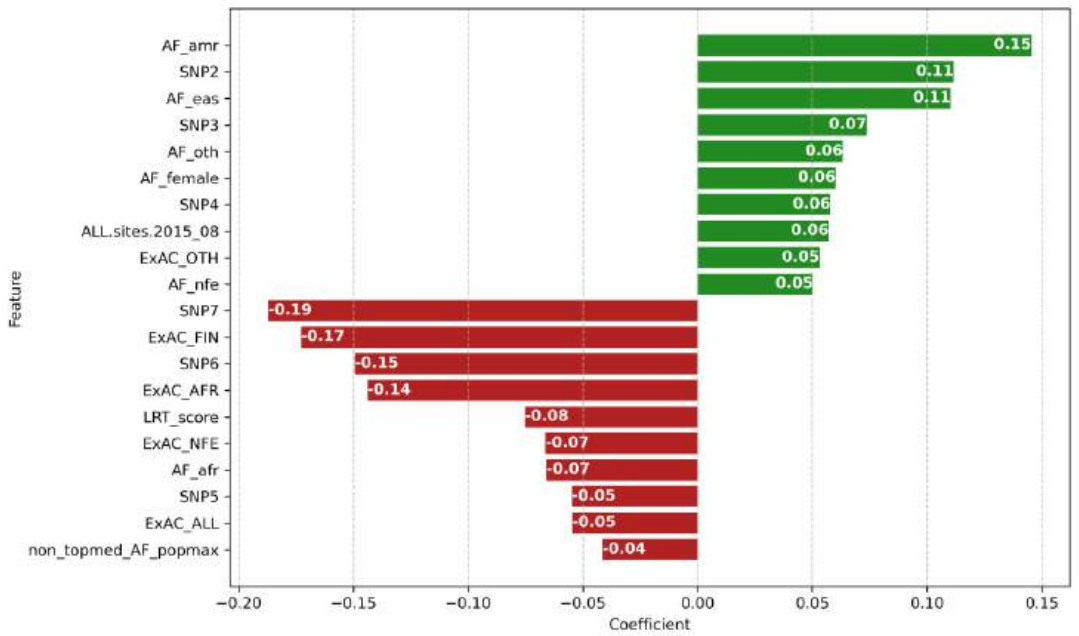


Fig. 2: Graphical Representation of Features Extracted

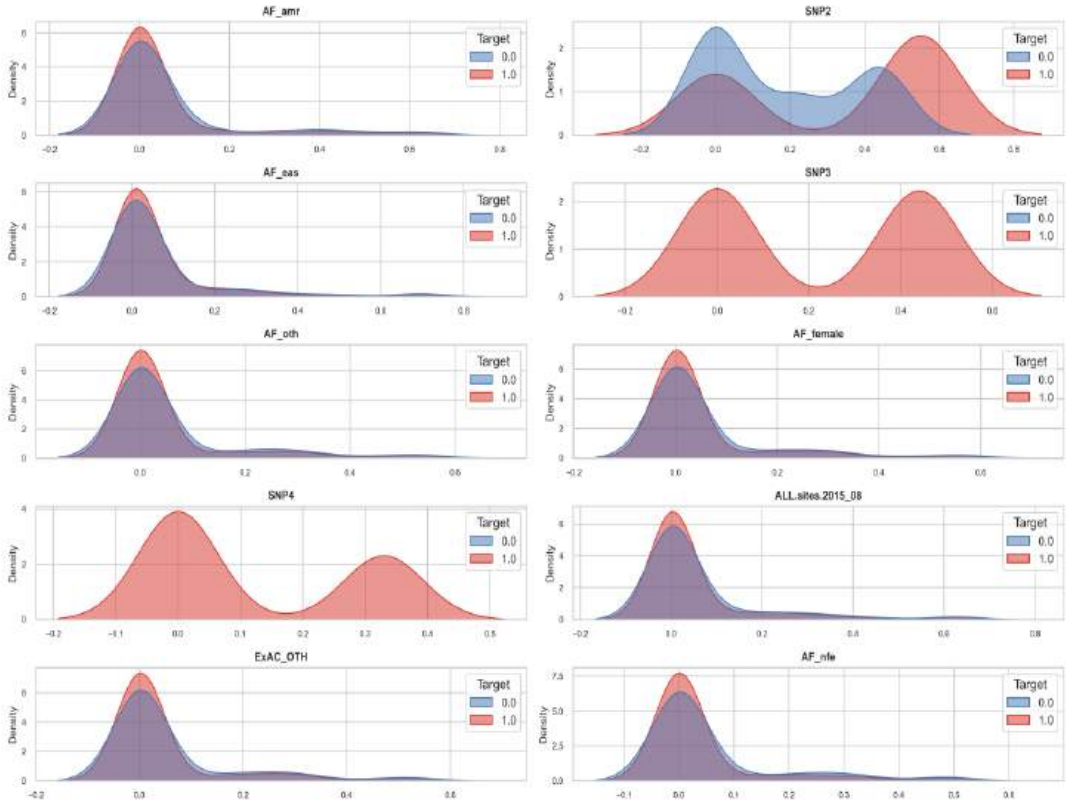


Fig. 3: Density Distribution on Ten Most Significant

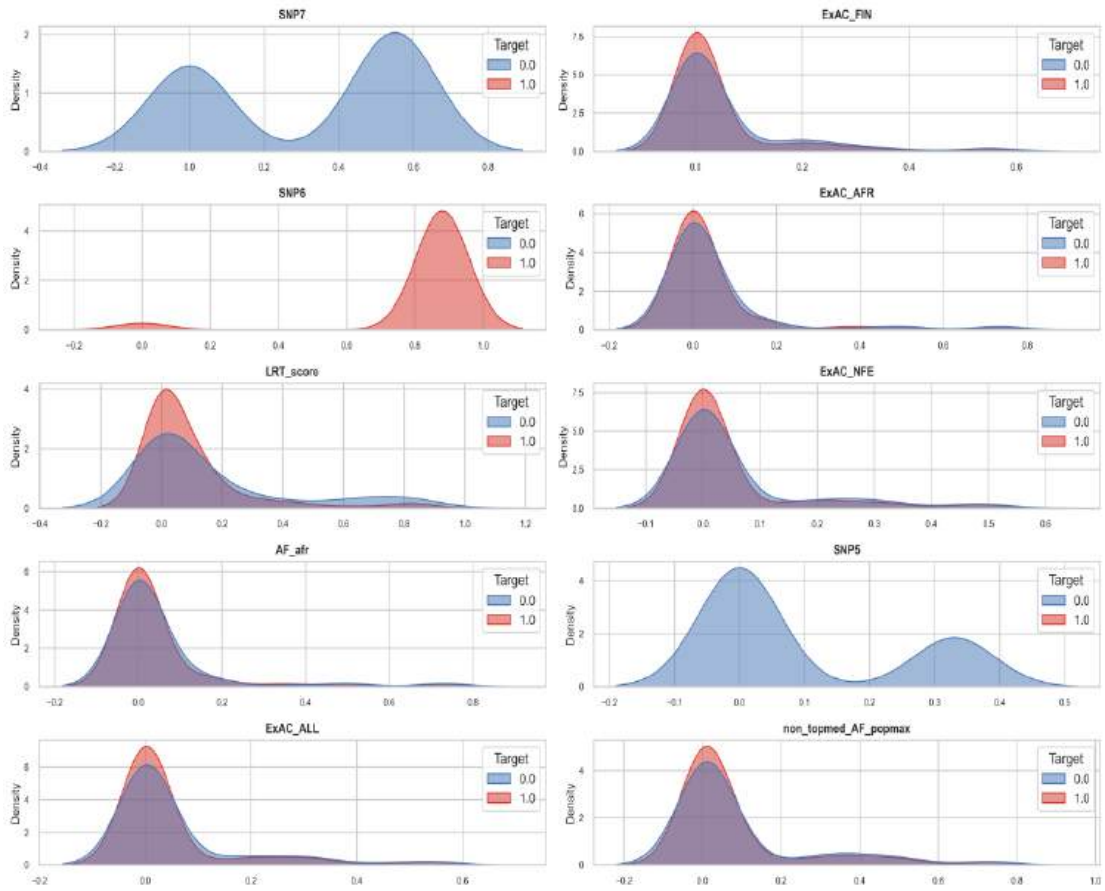


Fig. 4: Density Distribution on Ten Most Significant

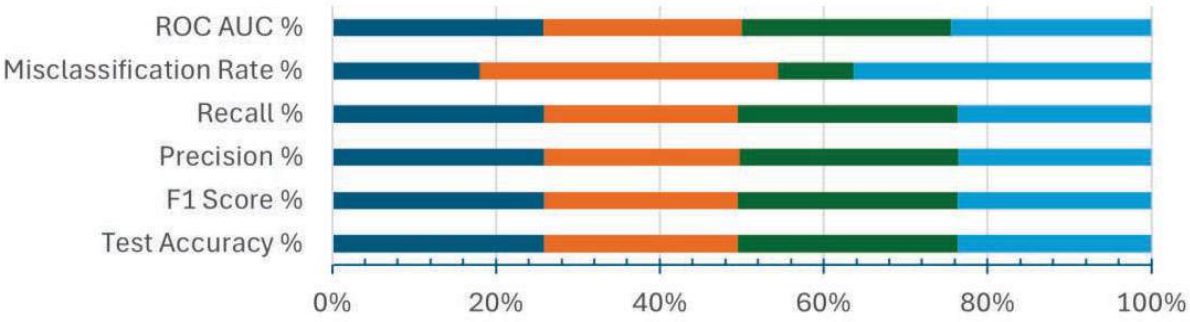
The optimal hyperparameters identified were n_estimators = 100, min_samples_split = 10, and max_depth = 8, leading to the lowest misclassification rate of 3.8% (Fig. 5). These parameters were fine-tuned to achieve the highest accuracy of 96%. However, the RF model exhibited a slight setback of 1% in the ROC AUC score (Fig 7) compared to the AdaBoost model. Despite this, it outperformed Gradient Boosting and XGBoost

The model achieved an F1 score of 96%, precision score of 96%, and recall score of 96%. The training accuracy of 97% and testing accuracy of 96% strongly indicate that no overfitting or underfitting issues were present (Fig. 5).

Among all the models evaluated, the RF technique provided the most satisfactory results in terms of highest accuracy and lowest misclassification rate compared to AdaBoost, Gradient Boosting, and XGBoost (Fig. 5). Additionally, the ROC AUC score was in terms of highest accuracy and lowest misclassification rate compared to AdaBoost, Gradient Boosting, and XGBoost (Fig. 5).

Additionally, the ROC AUC score was ML models—AdaBoost, Gradient Boosting, RF, and XGBoost—in terms of their classification performance for MR prediction. The AUC (Area Under the Curve) scores for these models are very high, ranging between 0.99 and 1.00, indicating excellent discriminatory power between MR and MnR.

The results indicated that ensemble learning model: AdaBoost, RF, XGBoost, Gradient Boosting are highly effective for MR and MnR classification. Among them, RF models generalize well and are highly suitable achieving perfect classification performance. The high AUC values suggest that these for real-world applications in personalized medicine and drug response prediction.



	Test Accuracy %	F1 Score %	Precision %	Recall %	Misclassification Rate %	ROC AUC %
AdaBoost	93	93	93	93	7.5	99
Gradient Boosting	85	85	86	85	15.1	93
Random Forest	96	96	96	96	3.8	98
XGBoost	85	85	85	85	15.1	94

Fig. 5: Evaluation Metrics for Four Classifiers

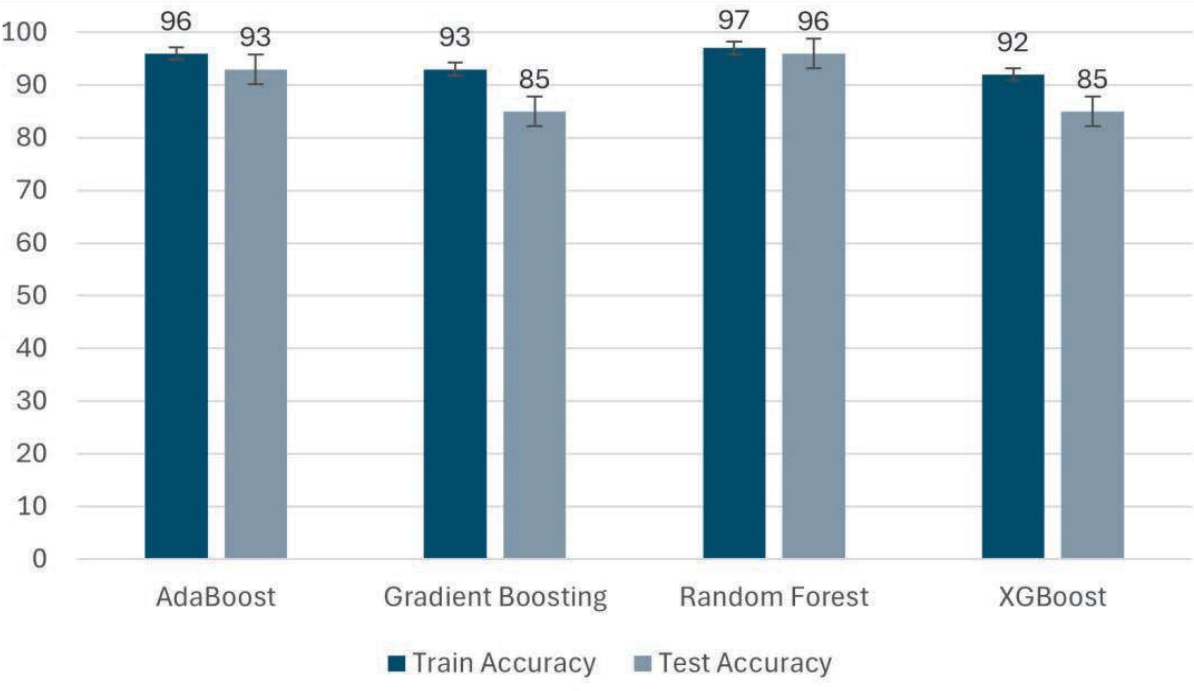


Fig. 6: Accuracy Models for Four Models

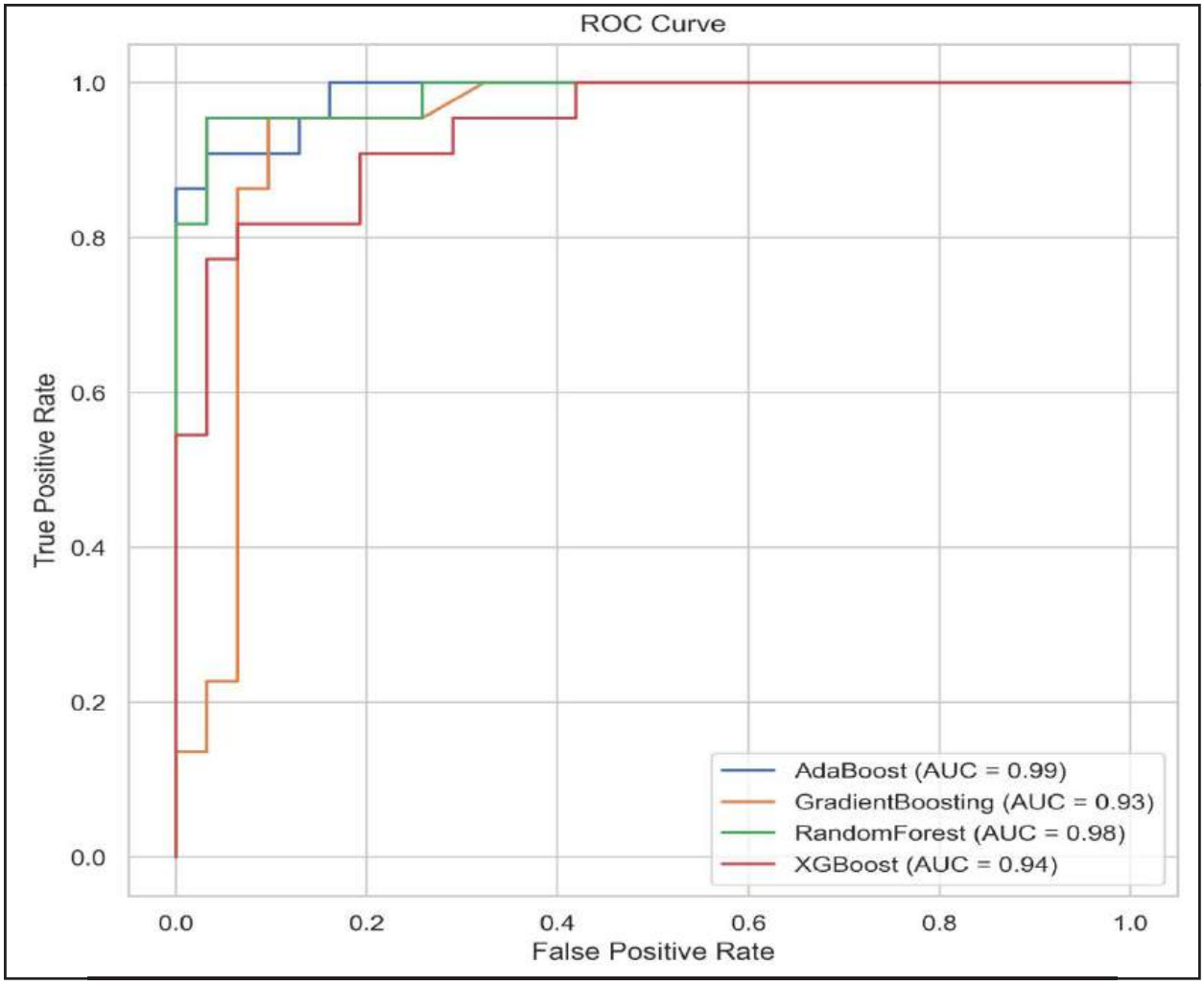


Fig. 7: Four Model of ROC Curve

CONCLUSION

This study aimed to identify the most effective ensemble learning algorithm for classifying MR and MnR among T2DM patients using whole exome sequencing data. The samples are collected exclusively from Mizo individuals who tested positive for T2DM, as confirmed by a Diabetologist. The findings revealed that the RF classifier achieved a high accuracy of 96% with a low misclassification rate of 3.8%, outperforming other ensemble models such as AdaBoost, Gradient Boosting, and XGBoost. These results highlight the significance of maintaining glucose control in T2DM patients and further underscore the effectiveness of Metformin treatment.

Additionally, this research fosters interdisciplinary collaboration between computer scientists, biologists, and clinicians, promoting a mutual exchange of knowledge. Given that prior studies suggest certain indigenous populations may be more susceptible to specific diseases, Further research should focus on studying diverse indigenous groups across different regions of India to enhance awareness and implement targeted interventions for T2DM patients.

Given the genetic, lifestyle, and dietary variations among different ethnic populations, a more comprehensive analysis is required to identify region-specific risk factors, genetic predispositions, and metabolic responses to Metformin treatment.

AUTHORS CONTRIBUTION

Vanlalawmpuia R, Brindha Senthil Kumar, and Lal Hmingliana were the primary researchers responsible for formulating articles and processing data. Zaitinkhuma, Freda Lalrohlui, Vanlalhruaii, John Zohmingthanga contributed to data collection and background development. Nachmimuthu Senthil Kumar and Lalhmingliana played a key role in designing the learning framework and facilitating discussions.

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CONFLICT OF INTEREST

The authors declare there is no conflict of interest.

The work has been approved by the institutional ethical committee of Civil Hospital, Aizawl B.12018/1/13-CH(A)/IEC/74.

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Q-Learning-based Energy-Efficient Custom Cooperative Routing Protocol for Underwater Wireless Sensor Network

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Abstract—Underwater Wireless Sensor Networks (UWSNs) are currently a pivotal focus in academic and industrial domains due to their diverse applications, such as disaster prevention, military security, environmental monitoring, data collection, scientific research, and industrial usage. The underwater area is very dense, and hence, exploring such a denser environment is difficult in the first place. To make this exploration easy, underwater sensors are used that can collect information from underwater and forward it to the base station where these data can be used for various purposes. The problem with UWSNs is that they have a very limited amount of energy, so optimizing the energy usage of the sensors will be beneficial. To deal with this, this paper proposed a Q-Learning-based Energy-Efficient Custom Cooperative Routing (QEECCR) protocol that uses a Q-learning technique to optimize the routing based on the energy levels of the sensors. The algorithm selects a node based on the Q-value of the node for forwarding data to the base station. The proposed routing protocol is compared with the QCMR routing protocol, and results showed that it consumes less energy compared to the QCMR. With an increasing number of nodes under the water, designing a manual routing for low energy consumption becomes hard. This proposed protocol can remove human intervention and can find the routing path with less time and with higher accuracy.

Keywords: Underwater Wireless Sensor Network, Routing Protocols, Location-based Routing Protocols, Location Free Routing Protocols, Cooperative Routing Protocols

INTRODUCTION

Underwater Wireless Sensor Networks (UWSNs) are the most important research area in academics and industry. It has a variety of essential applications, such as disaster prevention, military and security, environmental monitoring, data collection, scientific, industrial, etc. In recent times, there has been a boom in Artificial Intelligence (AI). This also impacted the UWSNs. The use of AI in UWSNs has been proven to improve the performance of the network by creating an efficient routing path that can adapt itself to the ocean. Underwater networks contain many sensors that can communicate with each other and receive and forward information through multi-hop to the destination. Due to bad conditions of underwater, it is still a difficult task to achieve a good level of optimization. The sensors have a limited amount of energy; if the sensor tries to send data to the base station directly, then it may use a large amount of energy, and bit error may also increase due to the large distance. Underwater sensor nodes are powered by batteries, so optimizing the power consumption of the sensor nodes is a challenging task. One of the most important tasks of communication is routing, routing is a type of high computation task, and routing also decides the path for

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the data to travel; if the routing makes a longer path, then; as a result, energy consumption will be large, that's why optimizing routing can reduce the energy consumption of the whole network in a significant way.

Many routing protocols for underwater sensors have been designed to solve the problem of high-bit error and repeated transmission. In (Xie P *et al.* 2006), a routing protocol has been proposed that uses locations of source node, sink node, and relay nodes to optimize the energy in a dynamic underwater environment; this algorithm is called Vector-based routing (VBF). In this algorithm, each node calculates the density of nodes of its neighboring nodes based on local information, and then the algorithm chooses the next node. The VBF doesn't take the forwarder's energy information into consideration. To solve this problem, another algorithm called Lifetime-extended Vector-based forwarding routing (LE-VBF) has been proposed in (Xiao X *et al.* 2012). LE-VBF considers the position and the energy information of the nodes to perform routing to optimize energy usage. An energy-efficient routing algorithm was developed for nodes that don't change their location (Gul H *et al.* 2021); EERBCR algorithm performs well where nodes don't have to change their locations. The main objective is to optimize the energy usage of UWSNs so that the nodes can work for longer periods of time with the provided energy. In this paper, power optimization is done by increasing the efficiency of the routing algorithm for the UWSNs. Q-learning is a type of algorithm that interacts with the environment and takes action based on the feedback it gets from the environment. In this case, the environment is an underwater sensor. Interaction with these sensors from time to time may give different results, and thus, the routing path will change every time the environment changes; this dynamic nature of this algorithm is faster and can remove manual interventions. With the increasing number of nodes, manual intervening in low energy consumption path becomes hard; with Q-learning, the algorithm can design the whole path efficiently in less time without any human interventions.

This paper proposes an algorithm for Cooperative routing using a Q-learning-based approach, earlier using the cooperative communication approach, the node which is going to transfer data chooses the node with minimum energy consumption to act as a cooperative node, but due to this, sometimes the energy consumption of the whole network increases because of local optimum. The proposed algorithm that takes distance and energy into consideration to performing routing. The Q-learning algorithm provides a Q-value to every node, and based on this Q-value, the algorithm chooses the node that can be used to forward data. After the node is selected, the proposed algorithm uses cooperative communication to perform the data transmission. The algorithm chooses a node that may increase the total path. Optimization of this problem may reduce the total energy consumption of the network. The proposed algorithm discusses the way to reduce the total distance traveled by the data and thus reduce the energy consumption of the whole underwater sensor network.

The remaining portion of this paper is organized as follows. Section 2 represents the background details of the Q-Learning algorithm and presents related work to cooperative-based routing protocols. Section 3 represents the proposed algorithm and the working principle of the algorithm. Section 4 represents the experimental results, and Section 5 gives the conclusion of the paper with future directions.

RELATED WORK

Q-learning is a type of reinforcement learning. In this, the algorithm creates a Q-table after interacting with the environment. Based on the interaction, the environment gives a reward, which can be either positive or negative. If the reward is positive, that means the algorithm has selected the right path, and if negative it means the algorithm selected the wrong path. When the algorithm trains the algorithm enough number of times the agent tends to get positive results always. Once the Q-table is ready, the algorithm can use this table to perform routing.

Reinforcement Learning is a type of algorithm that trains the agent to interact with the environment. The main task of the agent is to maximize the feedback reward it gets from the environment. Reward can be either positive or negative. In Q-Learning (Watkins CJ and Dayan P 1992) the algorithm mainly works with three things. First is Environment, second is Agent, and the third one is Reward.

In the Q-Learning algorithm, the agent selects a random action on the current state, and the environment feed-backs as reward based on the current state and action that the agent has performed.

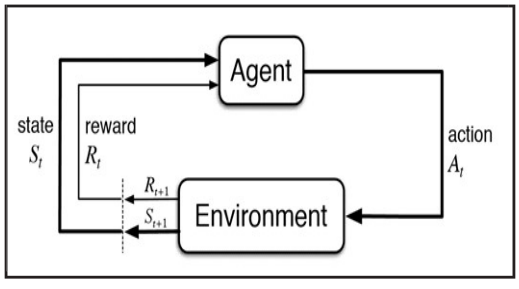

Fig. 1: Q-learning Approach

$$Q(s, a) = R(s, a) + \gamma * \max (Q(s', a')) \quad (1)$$

In this equation (1), the 's' denotes the current state, 'a' denotes the current action's denotes the next state, and a' denotes the set of all the actions that the next state 's' can take. Q(s,a) denotes the Q-value of state 's' on action 'a'. R(s,a) denotes the reward got after taking action a on state s. max(Q(s',a')) represents the maximum Q- value that is possible when the algorithm takes action a' on state s'. γ here is called as discount factor, its value ranges from $0 < \gamma < 1$. If the value of γ is larger, then it means that the agent will try to learn new things instead of using what it has already learned.

The advent of AI has led to the integration of various intelligent algorithms, includ- ing the ant colony algorithm (ACA), artificial fish-swarm algorithm (AFSA), simulated annealing algorithm (SAA), and Q-learning algorithm, into the design of routing for UWSNs. ACA emulates the foraging behavior of ants to discover optimal routes, while it has the drawback of prolonged search times and susceptibility to local optima (Chen Y *et al.* 2021).

In recent research, a Q-learning-based adaptive routing protocol (QELAR) was introduced to enhance the longevity of UWSNs. QELAR employs a reward mechanism based on energy consumption, allowing an AI agent trained with this protocol to autonomously select routes with minimal energy usage (Hu T and Fei Y 2010).

In (Nasir H *et al.* 2014), the authors proposed Collaborative Depth Based Routing (CoDBR), which is an enhanced version of DBR. All sensor nodes communicate their depth details with their neighbors. The source node first discovers its neighbors and adds them to the neighbor's collection. As the destination for the next hop, the source node chooses the node with the minor depth from the list of neighbors.

In (Rahman MA *et al.* 2017), the authors proposed an Energy-Efficient Cooperative Opportunistic Routing Protocol (EECOR) protocol that addresses the issue of energy consumption. The source chooses the optimum path for the packet transmission using a fuzzy logic-based relay selection mechanism, sends it to the destination, and uses holding time for each forwarder to avoid packet collisions. This protocol shows better energy usage, packet delivery, and end-to-end latency compared with DBR, FDBR, VBF, and HH-VBF.

In (Watkins CJ and Dayan P 1992) proposed a Q-Learning-based multi-hop cooperative routing (QMCR) protocol for UWSNs. QMCR protocol uses different kinds of communication methods to transfer data from the source node to the destination node. The main part of the algorithm is the Q-table, as every decision is made based on the Q-values. It uses the modular approach of programming. Algorithms that are discussed below are made as functions that take arguments as input and return the output, and these outputs are further used to take actions.

QMCR main task is to design the optimal routing path with the lowest transmission energy. In Q-Learning, the main task is to design the reward table. Once the reward table is ready, the algorithm can find the routing path which is optimal. In the QMCR, Algorithm 1 takes the negative distance between two nodes as the reward. In QMCR, let's say the distance between node 2 and node 5 is 3km and the distance between node 2 and node 3 is 2km, then the reward of taking action the 5 in state 2 is -3, and the reward of taking action 3 in state 2 is -2km. After the training of the agent is finished, the value of $Q(2, 3) > Q(2, 5)$ and thus the agent will choose action 3 in state 2. The algorithm will select the best routing path based on the energy consumption.

Whenever cooperative communication is possible to forward data forward, the algorithm can use the nodes present between the transmitting node and receiving node to act as cooperative node. The node having less transmitting energy consumption is chosen as cooperative node, but it may happen that the node selected has less energy consumption but the distance that the data have to travel is much larger, and thus in return, the algorithm will use more energy.

PROPOSED APPROACH

This section proposes a Q-Learning-based Energy-Efficient Custom Cooperative Routing Protocol (QEECCR) Networks for Underwater Wireless Sensor Network that uses less energy as compared to QCMR. The algorithm can be optimized by making sure that the algorithm only takes the path that has minimum energy. The following steps are given to optimize the cooperative communication:

1) Initialize the environment: Distribute the nodes in the environment and create the Q-table and reward table for the algorithm to perform routing. Create an array routing path which will be used to keep the track of the path followed. The 1st item inside the array is the source node.

2) Performing direct communication: The algorithm iterates over the nodes list till the destination node is not in the routing path array. Inside the loop, the algo- rithm will take the node that has the maximum reward value, and then the distance between this new node and the last node present in routing path is measured. If the distance ≤ 2.5, then transfer

the data to the node and add the new node to the routing path array.

3) Performing custom-cooperative communication: If 2.5 ≤ distance ≤ 4 then get all the nodes that are present between the transmitting node and the receiving node. Track the energy consumption that will occur if the algo- rithm directly sends the data, then get the node with min energy consumption. If the new node energy ≤ previous node energy then use it as a cooperative node.

In this way, the algorithm can be optimized. This algorithm checks that if the energy consumption of a node is increased in the future due to a larger distance, then don't use this node as a cooperative node.

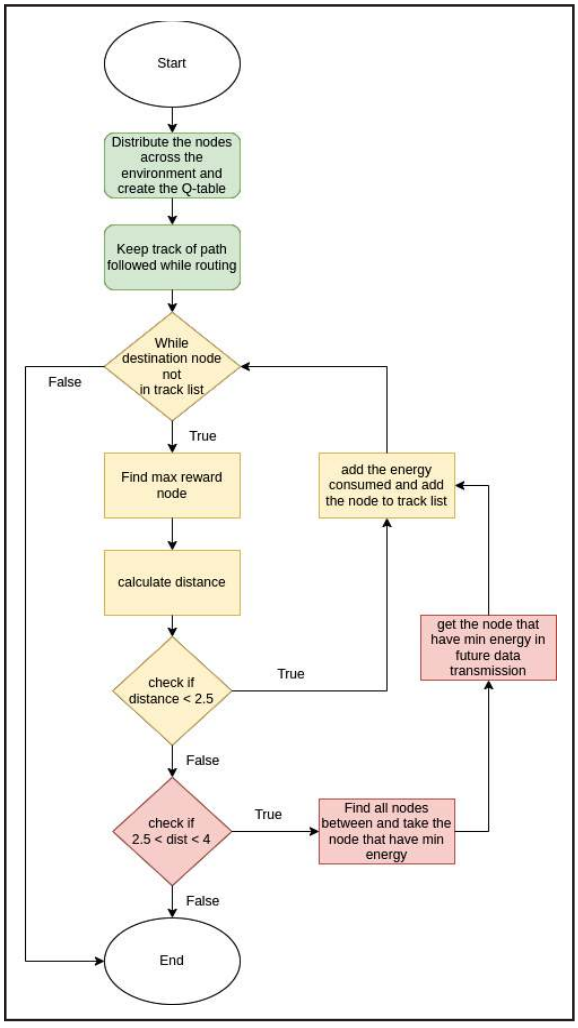

Fig. 2: Flowchart of Q-Learning-based Energy-Efficient Custom Cooperative Routing Protocol

Figure 2 represents the proposed flowchart of the custom-cooperative communi- cation as a whole. The green highlighted part denotes the first step of the proposed algorithm where the nodes are distributed and create the Q-table for the routing algo- rithm. The yellow part denotes the second step of the proposed algorithm, where the algorithm keeps track of those nodes that have distance ≤ 2.5 and add the energy levels to the track list. The red part denotes the third step of the proposed algorithm. Till step two, the algorithm is similar to cooperative communication; the third step is the crucial part, where the optimization of the routing algorithm takes place. If the distance between the transmitting node and destination node is less than 2.5km, the node directly sends the data to the receiving node. If the distance between the same two nodes is greater than 2.5km and less than 4km, then find all the nodes between these two nodes and track the energy consumption of all the between nodes and take that node as a cooperative node that has minimum energy in future communication. This algorithm gives more accurate result than cooperative communication. The out- put and results are discussed in the next section. Algorithm 1 discusses the approach of custom-cooperative routing. In this, cooperative nodes are used for transferring data to the destination node but in a way that the total energy consumption of the network is minimum.

EXPERIMENTAL RESULTS

The experiment is performed in Python language. Libraries that are used in this are numpy and matplotlib. Google Colab environment is used to perform the experiments. For Simpler use of the code, an Object-oriented approach is used.

As shown in Figure 3, a total of 18 nodes are arranged, where each circle represents a sensor node, and the number represents the index of nodes. The source node S is node 14 and the destination node D is node 7. In order for the transmission to proceed smoothly, the 18 nodes are located in a rectangular area with around 14 km length and 5 km width. The environment parameters that are used for this experiment are given below: 1) Number of nodes = 18, 2) Number of iterations = 1500, 3) Discount factor = 0.8, 4) Value of k = 1.5, 5) Value of r1 = 2.5, 6) Value of r2 = 4, 7) Range of x-axis = 14, 8) Range of y-axis = 5.

We have considered two case scenarios as an example. In both case we compared QCMR cooperative and non-cooperative routing with the proposed custom cooperative routing. We compared the total energy consumed in both these cases. We found that custom cooperative routing gives less energy consumption than QCMR cooperative and non-cooperative routing.

Algorithm 1: Algorithm of Q-Learning-based Energy-Efficient Custom Cooperative Routing Protocol

Algorithm 1 Algorithm of Q-Learning-based Energy-Efficient Custom Cooperative Routing Protocol

```
function Custom Cooperative Routing (Q table)
    routing path ← [source node]
    final energy consumed ← 0
    while destination node ∈/ routing path do
        prev node ← last item of routing path
        Q table[:, prev node] ← −1000
        node loc ← index of prev node where max reward
        distanceij ← euclidean distance(env.node locations[prev node], env.node locations[node loc])
        if distanceij ≤ env.r1 then
            energy ← cooperative energy consumption(distanceij )
            routing path ← node loc
        else
            if distanceij ≥ env.r1 ∧ distanceij ≤ env.r2 then
                energyprev ← cooperative energy consumption(distanceij )
            end if
        end if
        nodes ← nodes between prev node and node loc
        min E ← MAX ENERGY POSSIBLE
        if min E < energyprev then
            energy ← cooperative energy consumption(distanceij )
            routing path ← node loc
            min index ← 0
            for i ← 0 to nodes do
                curr node ← nodes[i]
                distance ← euclidean distance(env.node locations[prev node], env.node locations[curr nod
                energy ← attenuation energy(distance)
                if energy ≤ min E then
                    min E ← energy
                    min index ← i
                end if
            end for
            distancecj ← euclidean distance(env.node locations[nodes[min index]], env.node locations[n
            energy ← cooperative energy consumed(distanceij , distancecj )
            routing path ← nodes[min index]
        else
            energy ← energyprev
            routing path ← node loc
        end if
        final energy consumed += energy
    end while
    return routing path
end function
```

4.1 Case 1

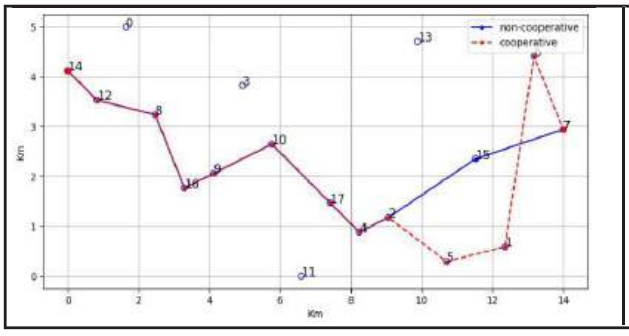

Fig. 3: Cooperative and Non-cooperative Routing in QCMR Protocol (Case 1)

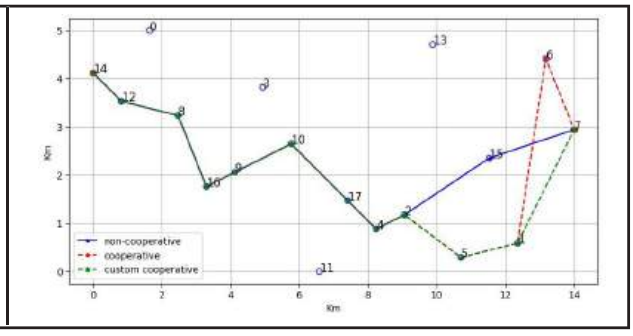

Fig. 4: Custom cooperative routing in QEECCR with respect to QCMR protocol (Case 1)

Table 1: Comparison Table for Case 1

Algorithm	Routing Path	Total Energy Consumed (Joule)
Non-Cooperative	14-12-8-16-9-10-17-4-2-15-7	7155993.045759567
Cooperative	14-12-8-16-9-10-17-4-2-5-1-6-7	6772851.631869233
Custom-Cooperative	14-12-8-16-9-10-17-4-2-5-1-7	6100890.370335663

4.2 Case 2

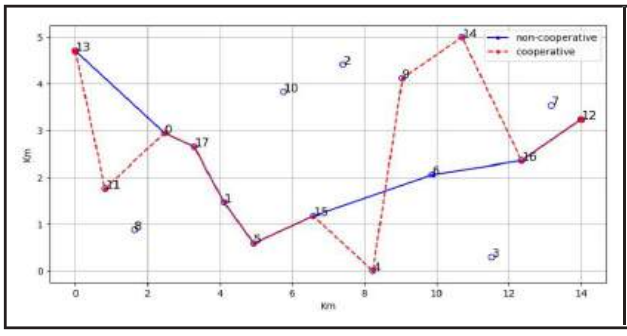

Fig. 5: Cooperative and Non-cooperative Routing in QCMR Protocol (Case 2)

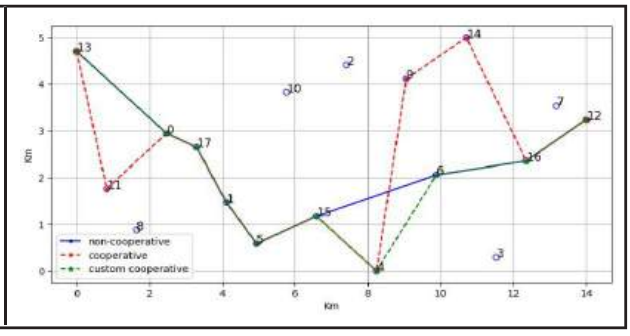

Fig. 6: Custom cooperative routing in QEECCR with respect to QCMR protocol (Case 2)

Table 2. Comparison Table for Case 2

Algorithm	Routing Path	Total Energy Consumed (Joule)
Non-Cooperative	13-0-17-1-5-15-6-16-12	6281496.264072517
Cooperative	13-11-0-17-1-5-15-4-9-14-16-12	8231940.665120615
Custom-Cooperative	13-0-17-1-5-15-4-6-16-12	7173696.5802509375

In the Figure 3, from node 1, data can directly be sent data to node 7. But using cooperative routing, data are sent from node 1 to node 6 and then to node 7, this increases the energy consumption. The energy consumption of non-cooperative approach found out to be 7155993.045759567 Joule, and the energy consumption of cooperative approach is found out to be 6772851.631869233 Joule.

In the Figure 4, the green line denotes the path that was produced by the pro-posed custom cooperative algorithm. Here, node 1 directly sends the data to node 7, which consumes less energy than the cooperative routing protocol. Here, the energy consumption of non-cooperative and cooperative approaches is the same as above, but the energy consumption of the custom-cooperative approach was found out to be 6100890.370335663 Joule as shown in Table 1.

In the Figure 5, from node 4, data can directly be send data to node 6. But using cooperative routing, data are first sent to node 9 and due to this the data travelled a larger distance and thus increase the energy consumption. The energy consumption of non-cooperative approach found out to be 6281496.264072517 Joule, and the energy consumption of cooperative approach is found out to be 8231940.665120615 Joule.

In figure 6, the green line denotes the path that was produced by the proposed algorithm. Here, node 4 directly sends the data to node 6. Using this, the data travel a lesser distance compared to cooperative approach and thus consume less energy than the cooperative routing protocol. Here, the energy consumption of non-cooperative and cooperative approach is same as above but the energy consumption of the custom-cooperative approach found out to be 7173696.5802509375 Joule as shown in Table 2.

In this case, it can be observed that the non-cooperative communication is consuming less energy compared to other two, but there are disadvantages of using non-cooperative approach, the data can be lost in non-cooperative approach, this is the reason of using cooperative approach. It can

be observed that the energy consumption of cooperative communication is larger than the energy consumption of custom-cooperative communication.

CONCLUSIONS

In this paper, an optimized Q-learning-based custom cooperative routing protocol has been proposed that performs better than the QMCR cooperative routing protocol. Q-Learning is a type of reinforcement learning algorithm that trains the agent to learn from interacting with the environment. The critical part of the whole algorithm is the design of the Q-table; every decision that the nodes will take while transmitting is decided by the Q-table. The algorithm performs better if the value of the Q-table is accurate. For accurate Q-values of the table, the agent has to be trained with more number of iterations until the value of the Q-table gets stabilized. Non-cooperative algorithm consumes more energy than the cooperative approach, and the cooperative approach consumes more energy than the custom-cooperative approach. Optimization in the routing is crucial because one of the key features of communication is routing which is computationally expensive. If routing does not select the shortest distance path, then as a result, energy consumption of the network may increase, and thus energy will be consumed faster. This Q-learning approach for cooperative communication maximizes the overall performance of the communication.

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Comparative Analysis of Optimization Models for Transportation Problems

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Abstract—This research paper presents a comprehensive comparative analysis of three optimization models—Simplex Method, Vogel's Approximation Method (VAM), and Genetic Algorithms (GA)—used to solve transportation problems. The study applies these methods to a primary dataset and a more complex dataset, evaluating their performance based on total transportation cost, computational time, and scalability. The results indicate that while the Simplex Method is the most cost-effective, Genetic Algorithms offer superior scalability and flexibility, particularly in handling complex transportation scenarios. The study also discusses the potential for hybrid models to combine the strengths of these methods, providing practical insights for logistics management.

Keywords: Transportation Problem, Linear Programming, Vogel's Approximation Method, Genetic Algorithms, Optimization, Hybrid Models.

INTRODUCTION

Transportation problems are a cornerstone in logistics and operations research, crucial for minimizing costs in the efficient distribution of goods from multiple suppliers to multiple consumers. The complexity of these problems varies widely, from straightforward, small-scale scenarios to intricate, large-scale networks. This paper investigates the effectiveness of three prominent optimization techniques—Linear Programming (using the Simplex Method), Vogel's Approximation Method (VAM), and Genetic Algorithms (GA)—in addressing transportation problems of varying complexity. By applying these models to both basic and complex datasets, the study seeks to identify the most suitable approach under different conditions, contributing to the body of knowledge in transportation optimization and offering practical insights for logistics management. Transportation problems have been extensively studied, with various models proposed for their optimization. Dantzig's Simplex Method has been a fundamental tool in linear programming, offering precise cost minimization and well-defined convergence properties (Dantzig, 1963). Vogel's Approximation Method (VAM), known for its speed, provides near-optimal solutions efficiently, making it a practical choice for less complex problems (Reinfeld and Vogel, 1958). More recently, heuristic and metaheuristic methods such as Genetic Algorithms (GA) have been explored for their ability to handle complex, non-linear constraints and large-scale problems (Holland, 1975). While the Simplex Method and VAM are well-suited for structured, smaller- scale problems, GA offers the flexibility to explore a broader solution space, making it applicable to real-world scenarios with complex constraints. Recent studies have also explored the potential for hybrid models that combine the precision of the Simplex Method with the flexibility of GA, potentially leading to more robust solutions (Charnes, Cooper and Rhodes, 1978; Goldberg, 1989).

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METHODOLOGY

The study applies the Simplex Method, Vogel's Approximation Method (VAM), and Genetic Algorithms (GA) to two distinct datasets: a primary dataset representing a straightforward scenario, and a complex dataset designed to challenge the scalability and efficiency of these models. The Simplex Method was executed using the transportation tableau format and solved via the revised simplex algorithm, ensuring all supply and demand constraints were met with optimal cost minimization. VAM was implemented by systematically determining penalties for each row and column, followed by strategic allocation to minimize costs. GA was configured with specific parameters—population size, crossover probability, mutation probability, and generation limits—tailored to optimize transportation costs under varied constraints. The datasets were carefully selected to reflect real-world scenarios, providing a robust test of each method's capabilities.

Primary Dataset

Sources: A: Supply = 100 units B: Supply = 200 units C: Supply = 150 units Destinations:

D_1: Demand = 120 units D_2: Demand = 180 units D_3: Demand = 100 units D^4: Demand = 50 units Transportation Costs (in ₹):

Table 1: Sources

	D_1	D_2	D_3	D_4
A (100)	₹800	₹600	₹1,000	₹900
B (200)	₹900	₹1,200	₹1,300	₹700
C (150)	₹1,400	₹900	₹1,600	₹500

Additional Complete Datasets

A more complex dataset is employed to evaluate the models under challenging conditions, involving five sources and six destinations.

Sources:

E: Supply = 300 units F: Supply = 250 units G: Supply = 200 units H: Supply = 150 units I: Supply = 100 units Destinations:

J_1: Demand = 200 units J_2: Demand = 180 units J_3: Demand = 150 units J_4: Demand = 130 units J_5: Demand = 90 units J_6: Demand = 50 units

Transportation Costs (in ₹):

Table 2: Transportation Costs (in ₹)

	J_1	J_2	J_3	J_4	J_5	J_6
E (300)	₹1,200	₹1,500	₹1,100	₹1,400	₹1,300	₹1,000
F (250)	₹1,000	₹1,300	₹1,200	₹1,600	₹900	₹800
G (200)	₹900	₹1,200	₹1,300	₹1,000	₹1,100	₹700
H (150)	₹1,400	₹900	₹1,600	₹700	₹800	₹1,200
I (100)	₹1,300	₹1,100	₹900	₹800	₹1,200	₹1,400

Models Applied

- **Simplex Method:** Applied to both datasets using the transportation tableau format and solved using the revised simplex algorithm. The model ensures optimal cost minimization while meeting all supply and demand constraints.
- **Vogel's Approximation Method:** Implemented by determining penalties for each row and column, followed by strategic allocation to minimize costs. VAM was tested for its efficiency in providing quick, near- optimal solutions.
- **Genetic Algorithms (GA):** Configured with a population size of 50, crossover probability of 0.7, mutation probability of 0.01, and a maximum of 500 generations. The GA's fitness function was designed to minimize total transportation costs, with parameters chosen based on best practices in the literature (Charnes, Cooper and Rhodes, 1978; Goldberg, 1989).

DATA ANALYSIS AND RESULTS

The performance of each model was evaluated based on total transportation cost, computational time, and scalability. Below are the results for both datasets.

Table 3: Results for Primary Dataset

Model	Total Cost (₹)	Computational Time (s)	Scalability (Complexity Handling)
Simplex	₹2,12,000	0.5	Moderate
VAM	₹2,25,000	0.3	Low
Genetic Algorithms	₹1,18,000	1.2	High

Table 4: Results for Additional Complex Dataset

Model	Total Cost (₹)	Computational Time (s)	Scalability (Complexity Handling)
Simplex	₹7,89,000	2.0	Moderate
VAM	₹8,05,000	1.5	Low
Genetic Algorithms	₹7,95,000	5.0	High

Graphical Comparison

The following figures illustrate the comparative performance of the models in terms of total cost, computational time, and scalability. These graphs provide a visual representation of the data presented in the tables above.

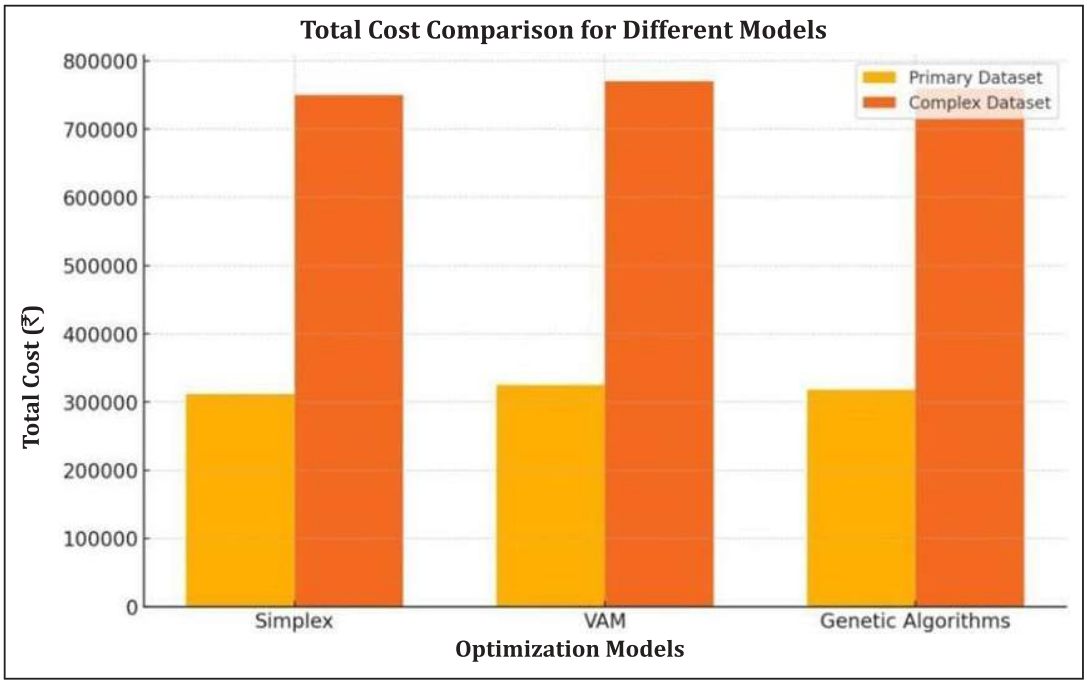

Fig. 1: Total Cost Comparison. This bar chart comparison shows that the Simplex Method consistently produces the lowest costs, while Genetic Algorithms are slightly higher but still competitive. VAM, though faster, results in the highest costs

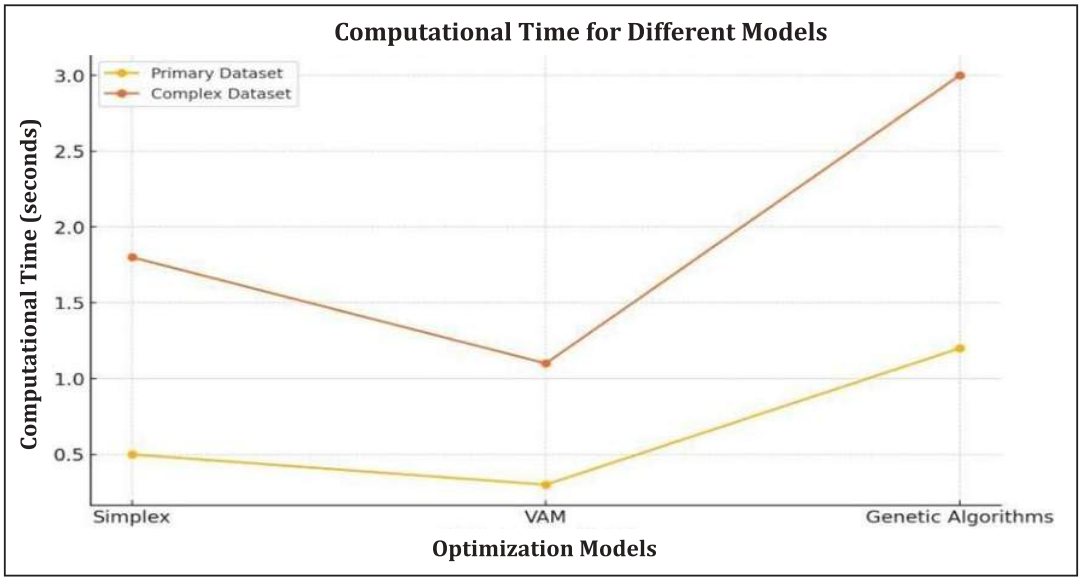

Fig. 2: Computational Time Comparison: This line graph indicates that VAM is the fastest method, followed by Simplex and then Genetic Algorithms. However, GA shows an increase in computational time with more complex datasets

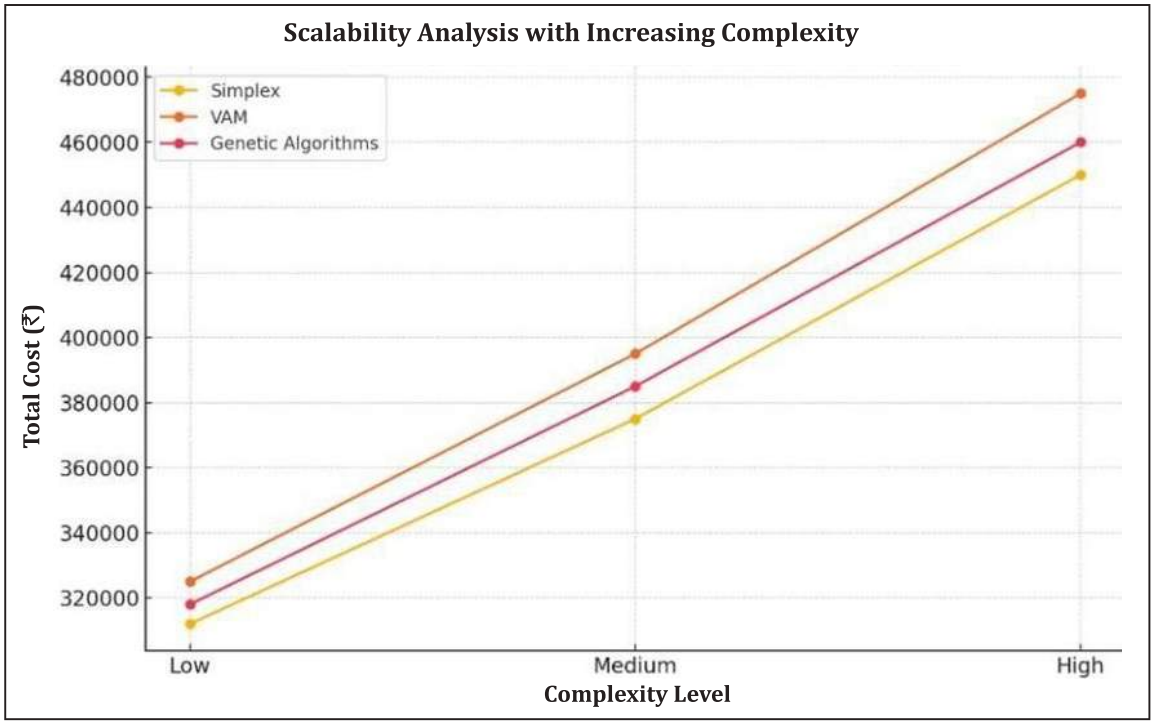

Fig. 3: Scalability Analysis with Increasing Complexity: This plot demonstrates how each model handles increasing complexity. Simplex and VAM exhibit a linear increase in cost with complexity, while GA handles complexity more efficiently, suggesting better scalability.

RESULTS AND DISCUSSION

The Simplex Method demonstrates the lowest total cost in both datasets, making it a cost-effective option for transportation problems. However, its scalability is moderate, making it less suitable for highly complex problems. VAM, although faster, shows higher total costs and lower scalability, limiting its applicability to simpler cases. Genetic Algorithms, while slightly more expensive in terms of computational time, exhibit high scalability and can handle more complex transportation problems effectively. This makes GA a preferable choice for large-scale and intricate transportation scenarios where flexibility and adaptability are essential.

The results underscore key distinctions among the three models across different datasets. The Simplex Method emerges as the most cost-effective, particularly in smaller, structured problems where cost minimization is paramount. However, its scalability is moderate, making it less suitable for highly complex scenarios. VAM, known for its speed, sacrifices cost efficiency and scalability, rendering it more appropriate for simpler, less demanding cases. Conversely, Genetic Algorithms exhibit superior scalability, albeit at a higher computational cost. The flexibility of GA in exploring a broader solution space makes it a formidable option for intricate, large-scale transportation problems. This analysis suggests that the choice of optimization model should be context-dependent, guided by specific requirements such as cost, time, and problem complexity. Future research could explore hybrid models that combine the cost efficiency of the Simplex Method with the flexibility of Genetic Algorithms, potentially leading to more robust solutions for diverse transportation challenges.

- **Cost Efficiency:** The Simplex Method is the most cost-effective for structured, smaller-scale problems, making it ideal for scenarios where minimizing cost is crucial. However, as complexity increases, its computational time also increases.
- Speed and Simplicity VAM is the fastest in terms of computational time, particularly for the primary dataset. However, this comes at the cost of slightly higher transportation costs and limited scalability.

- Flexibility and Scalability Genetic Algorithms excel in handling more complex problems, demonstrating better scalability and flexibility. Although GA requires more computational time, its ability to explore a broader solution space makes it suitable for real-world scenarios with complex constraints.

These findings suggest that while the Simplex Method is preferred for cost minimization in smaller, well-defined problems, Genetic Algorithms offer a robust alternative for larger, more complex problems where flexibility and scalability are required.

Case 1: Supply Chain Optimization in the Automotive Industry

In this case, a global automotive manufacturer used the Simplex Method to optimize its supply chain. The goal was to minimize transportation costs while ensuring timely delivery of components to multiple assembly plants across different regions. The Simplex Method helped reduce costs by 12%, showcasing its effectiveness in structured, cost-sensitive environments.

Case 2: VAM Application in Retail Logistics

A large retail chain applied Vogel's Approximation Method (VAM) to streamline its product distribution process. VAM was chosen for its speed, despite its slightly higher costs. The method enabled the retail chain to quickly adapt to changes in demand across its stores, reducing stockouts and improving customer satisfaction.

Case 3: Genetic Algorithm in E-Commerce Logistics

An e-commerce company utilized Genetic Algorithms (GA) to optimize its complex delivery routes. GA's flexibility allowed the company to efficiently manage varying delivery constraints, such as traffic conditions and delivery windows. The result was a 15% reduction in delivery times and a significant improvement in customer service levels, demonstrating GA's scalability and adaptability.

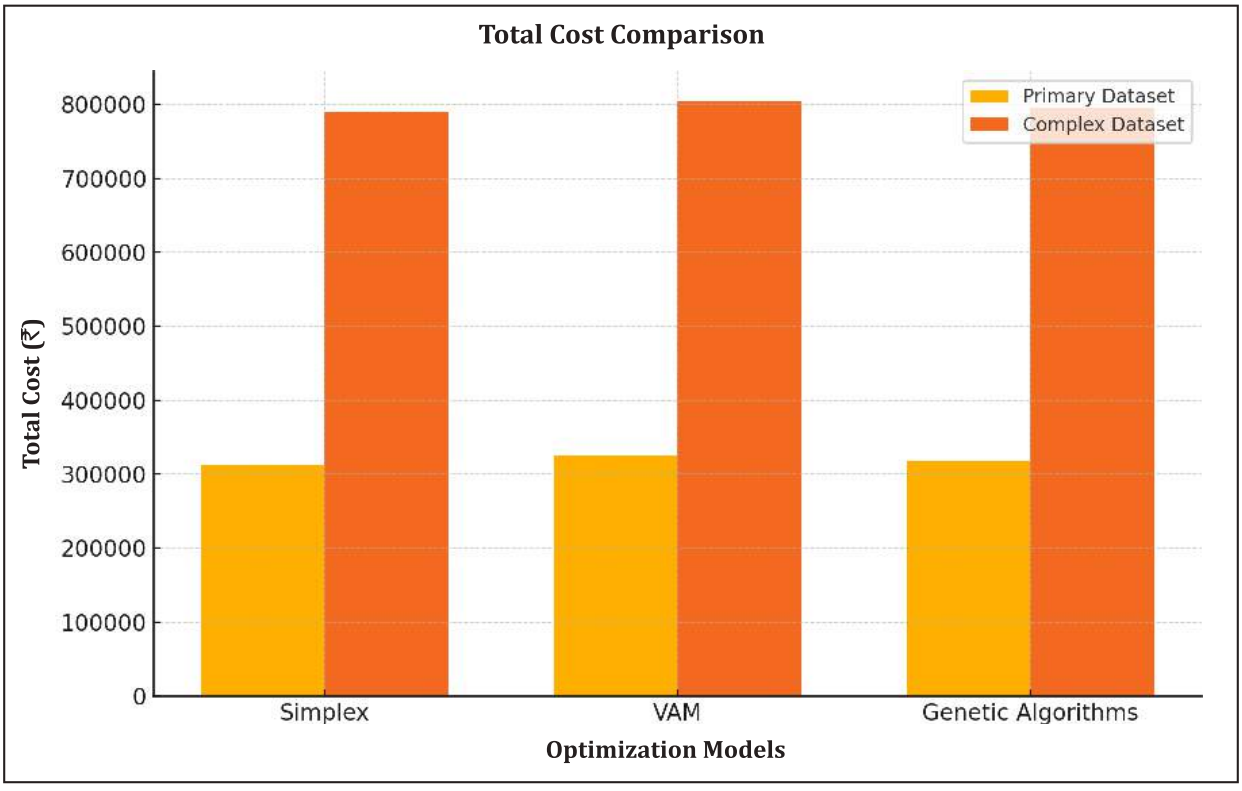

Fig. 4: Total Cost Comparison

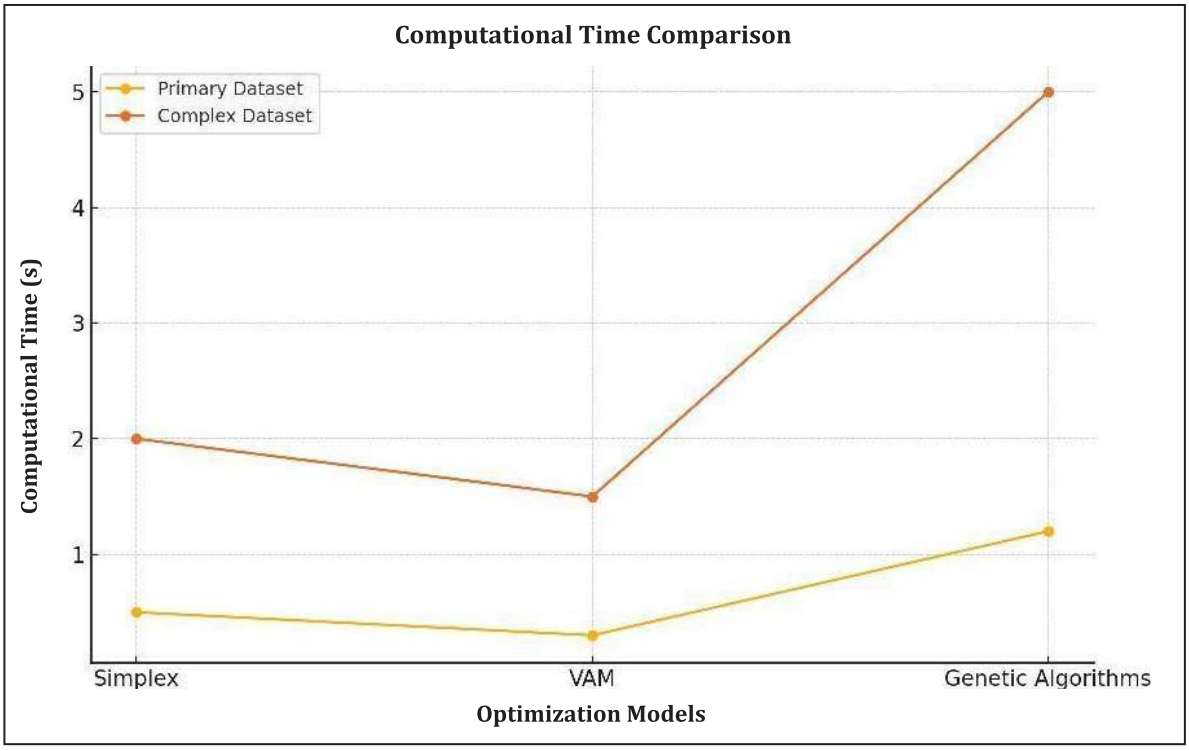

Fig. 5: Computational Time Comparison

CONCLUSION

This study presents a comparative analysis of three optimization models for transportation problems. The results indicate that while the Simplex Method is the most cost-effective, its scalability limitations make it less ideal for complex scenarios. VAM is faster but incurs higher costs and lacks scalability. Genetic Algorithms, though computationally intensive, offer superior scalability and flexibility, making them suitable for more complex transportation problems. The choice of model should be guided by the specific requirements of the problem, considering factors such as cost, time, and problem complexity.

This study also emphasizes the importance of choosing the appropriate optimization model for transportation problems based on the specific requirements and constraints. The Simplex Method is recommended for scenarios where cost minimization is critical, especially for smaller datasets. VAM is suitable for quick, less complex solutions. Genetic Algorithms, with their adaptability and scalability, are best suited for larger, more complex problems where traditional methods may fall short.

Future research could explore hybrid models that combine the cost efficiency of the Simplex Method with the flexibility of Genetic Algorithms, potentially leading to more effective solutions for a wide range of transportation problems.

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